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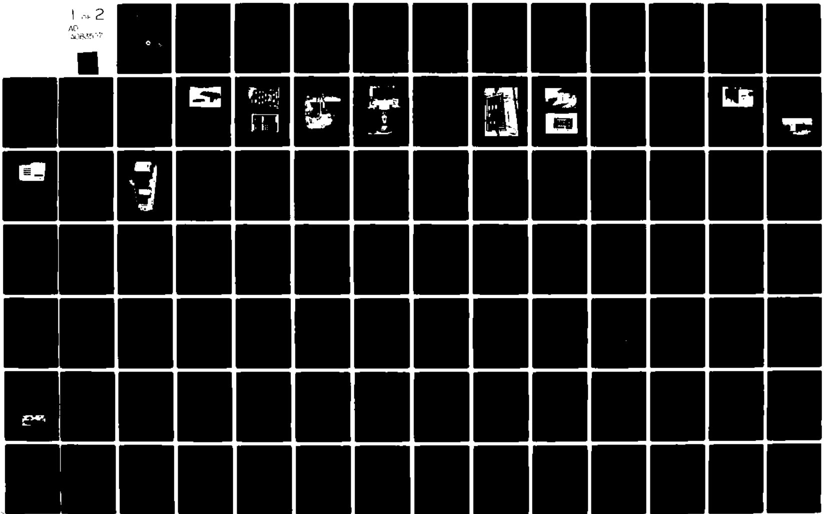

Report No. FAA-RD-80-9

LEVEL III

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NONDESTRUCTIVE TESTING FOR LIGHT AIRCRAFT PAVEMENTS

PHASE I

Evaluation Of Nondestructive Testing Devices

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JANUARY 1980
FINAL REPORT

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16. Abstract

Methodologies have been developed for nondestructive testing (NDT) and evaluation of air carrier airport pavements. This study, a two-phase program, addresses those pavements that are designed to support aircraft with gross weights of less than 30,000 lb. Phase I, reported herein, is to evaluate commercially available NDT devices with respect to operational characteristics, costs, transportability by cargo aircraft, accuracy, and reproducibility of measurements, and suitability for use in evaluating light aircraft pavements. The equipment evaluated included the Benkelman Beam, Dynaflect, Falling Weight Deflectometer, and Models 400, 510, and 2008 Road Raters. The WES 16-kip vibrator was used as a comparison device. Based on the evaluation parameters, the Dynaflect, Model 2008 Road Rater, and Falling Weight Deflectometer are evaluated applicable for testing light aircraft pavements.

17. Key Words
Nondestructive testing
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METRIC CONVERSION FACTORS

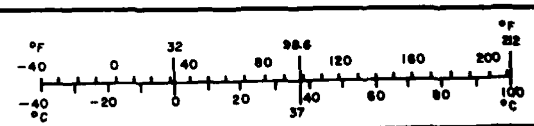
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This study, a two-phase program, was sponsored by the Federal Aviation Administration through Inter-Agency Agreement No. DOT FA78WAI-848, "Nondestructive Testing for Light Aircraft Pavements." Phase I of the study, which is reported herein, was conducted during the period April 1978 - July 1979 under the direction of Messrs. J. P. Sale, Chief, Geotechnical Laboratory (GL); R. G. Ahlvin, Assistant Chief, GL; R. L. Hutchinson, Pavement Program Manager; A. H. Joseph, Chief, Pavement Investigations Division; and J. W. Hall, Jr., Chief, Evaluation Branch, of the U. S. Army Engineer Waterways Experiment Station (WES). Messrs. J. L. Green, D. R. Elsea, and A. J. Bush III actively participated in the study. The report was prepared by Mr. Bush.

Acknowledgement is made to Dr. M. C. Wang and the Pennsylvania Transportation Institute for allowing the testing and providing data on the Pennsylvania Transportation Research Facility. Special thanks are also extended to Messrs. Gaylord Cumberledge, the Pennsylvania Department of Transportation; Paul Teng, the Mississippi State Highway Department; T. O. Edick, Region 15, Federal Highway Administration; and D. M. Greer and R. N. Stubstad, private consulting engineers, for the use of their nondestructive test devices.

Directors of the WES during the conduct of the investigation and the preparation of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

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INTRODUCTION

BACKGROUND

The Federal Aviation Administration (FAA) has sponsored several studies to develop methodologies for nondestructive testing (NDT) evaluation and overlay design for air carrier airport pavements. These studies, reported by Green and Hall,* Weiss,** and Yang,† all utilized the U. S. Army Engineer Waterways Experiment Station (WES) 16-kip (7.3-metric ton) vibrator, which applies a maximum peak-to-peak load on a pavement of 30,000 lb (133.4 kN). The WES 16-kip vibrator is considered undesirable for light aircraft pavements (design gross loading less than 30,000 lb (133.4 kN)) because this load may overstress the light aircraft pavement; smaller, less expensive, and more air-transportable equipment may provide an accurate evaluation for thinner pavements. Therefore, the FAA sponsored the research project described herein to evaluate the applicability of loads lighter than those produced by the WES 16-kip vibrator for testing light aircraft pavements.

The overall study of NDT for light aircraft pavements is a two-phase program. Phase I, which is reported herein, is for the evaluation of the applicability of light load devices for the NDT of light aircraft pavements. Phase II will develop a methodology for evaluation of light aircraft pavements based upon multilayered elastic models and limiting stress/strain criteria.

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* J. L. Green and J. W. Hall, Jr., "Nondestructive Vibratory Testing of Airport Pavements," Evaluation Methodology and Experimental Test Results, Vol 1, Report No. FAA-RD-73-305-1, Department of Transportation, Federal Aviation Administration, Washington, D. C., 1975.

** R. A. Weiss, "Pavement Evaluation and Overlay Design by Combined Methods of Layered Elastic Theory and Vibratory Nondestructive Testing" (in preparation), Department of Transportation, Federal Aviation Administration, Washington, D. C.

† N. C. Yang, "Nondestructive Evaluation of Civil Airport Pavements, Nondestructive Tests-Frequency Sweep Method, Part I," Report No. FAA-RD-76-83, Department of Transportation, Federal Aviation Administration, Washington, D. C., 1976.

PURPOSE

The purpose of Phase I of this study is to evaluate the loading required for the NDT of light aircraft pavements with respect to pavement response monitoring, equipment size and transportability, and equipment initial and operating cost.

SCOPE

The study will only include equipment that is commercially available and measures the structural characteristics of the entire pavement section by means of steady-state vibration, static loading or impact loading, and the resulting deflection measurements. Optimization of the loading devices will be accomplished through both laboratory and field pavement tests.

DESCRIPTION OF DEVICES TESTED

The devices evaluated during this investigation were limited to those that are commercially available to consulting engineers or airport administrators. They include the Benkelman Beam, the Dynaflect, the Falling Weight Deflectometer (FWD), and three models of the Road Rater. The WES 16-kip (7.3-metric ton) vibrator is also included since it was used as a standard to which these devices were compared. Table 1 presents the loading characteristics of all devices tested. The following paragraphs describe each device in detail.

BENKELMAN BEAM

The Benkelman Beam was developed at the WASHO Road Test* for the purpose of measuring the deflection of a flexible pavement under a loaded pneumatic tire. It consists of a lever rotating about a fulcrum that is fixed to a datum beam. The datum beam is supported on the pavement at three points. Figure 1 shows the dimensions of the beam.

A variation of the Benkelman Beam was developed by the California Highway Department in the form of a truck-mounted device. As the truck moves continuously along the road surface, a beam is alternately placed on the pavement and permitted to rest at a specific point until the wheel passes over the reference point. After this reading is taken, the beam is mechanically moved forward; the readings are repeated. The truck travels at a speed of one-half mile (0.8 km) per hour and is capable of taking continuous readings at 20-ft (6.1-m) intervals. This variation was not tested during this study primarily because it would not be air-transportable.

The procedure for testing with the Benkelman Beam was taken from the Asphalt Institute.** Basically, the toe of the beam is placed

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* Highway Research Board, "The WASHO Road Test, Part I," Report No. HRB Special Report 18, National Academy of Sciences, National Research Council, Washington, D. C., 1954.
__________, "The WASHO Road Test, Part II," Report No. HRB Special Report 22, National Academy of Sciences, National Research Council, Washington, D. C., 1955.

** Asphalt Institute, "Asphalt Overlays and Pavement Rehabilitation," Manual Series No. 17, College Park, Md., 1977.

Table 1

Nondestructive Test Device Loading Characteristics

	Frequency Hz	Dynamic Force Range lb_f	Static Weight lb_m	Contact Area in.^{2}	Maximum Dynamic Contact Pressure psi	Maximum Static Contact Pressure psi	Pavement Loading Device
Static							
Benkelman Beam	--	--	9,000	65.0	--	54.5	2 - 10.00 x 20.00 tires, 80 psi
Impulse							
FWD	16.7	0-13,200	556	110.0	120.0	4.6*	30-cm-diam plate, rubber covered
Vibratory							
Dynaflect	8	1,000	2,067	8.6	116.0	240.3	2 - 4-in.-wide, 16-in. O.D. polyurethane-coated rigid wheels spaced 20 in. C.C.
Model 400 Road Rater	(10, 20, 25, 30, 40)	0-800	1,100	56.0	14.2	19.6	2 - 4- by 7-in. rectangular pads
Model 510 Road Rater	(10, 20 25, 30, 40)	0-2,400	1,350	56.0	42.9	24.1	2 - 4- by 7-in. rectangular pads
Model 2008 Road Rater	5-50	0-8,000	4,000	254.0	31.4	15.7	18-in.-diam steel plate
WES 16-kip	5-100	0-30,000	16,000	254.0	118.0	63.0	18-in.-diam steel plate

Note. 1 lb_f = 4.448 N; 1 lb_m = 0.45 kg; 1 in.^{2} = 6.45 cm^2; 1 psi = 763 kg/m^2; 1 in. = 2.54 cm.

* When falling weight is released, the static weight is reduced by that weight (330 lb); therefore, the pressure would also be reduced to 1.9 psi.

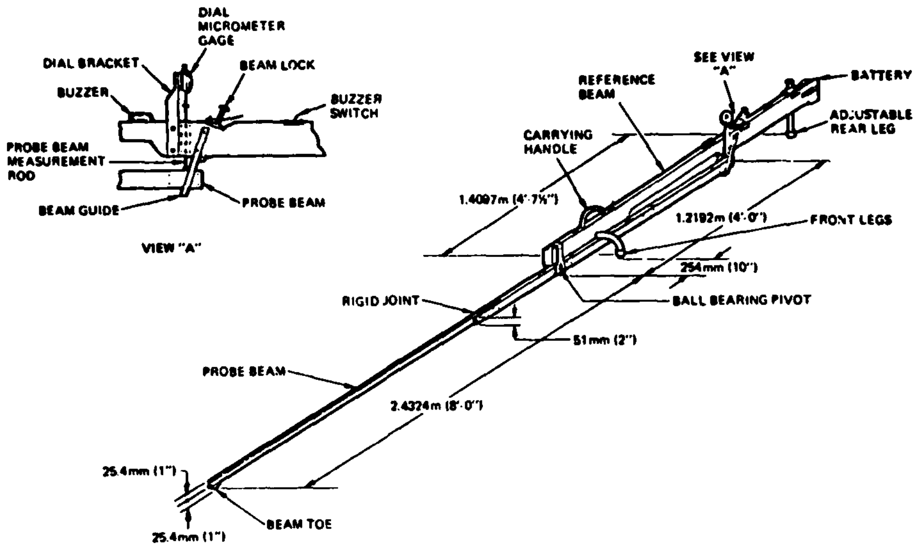

Figure 1. Benkelman Beam

between the dual wheels of a single axle loaded to 18,000 lb (8,615 kg). The dials are zeroed and the truck is driven forward at least 30 ft (9.1 m). The rebound deflection is then measured.

DYNAFLECT

The Dynaflect is an electromechanical system for measuring the dynamic deflection of a pavement caused by an oscillatory load. It is manufactured by SIE, Inc., Fort Worth, Texas. The trailer-mounted device (Figure 2) applies a 1000-lb (4448-N) peak-to-peak sinusoidal load to the pavement. This load is generated by two counterrotating masses that are rotating at a constant frequency of 8 Hz. The force is transmitted to the pavement through two 4-in.- (10.2-cm-) wide, 16-in.- (40.6-cm-) OD polyurethane-coated steel wheels spaced 20 in. (50.8 cm) apart. The Dynaflect applies a 2000-lb (907-kg) static weight to the pavement.

The pavement response to the dynamically applied load is measured with 210-ohm, 4.5-Hz geophones that are shunted to a damping factor of approximately 0.7. One geophone is located directly between the two steel wheels. The other four geophones are spaced at 1-ft (30.5-cm) intervals to the front of the trailer.

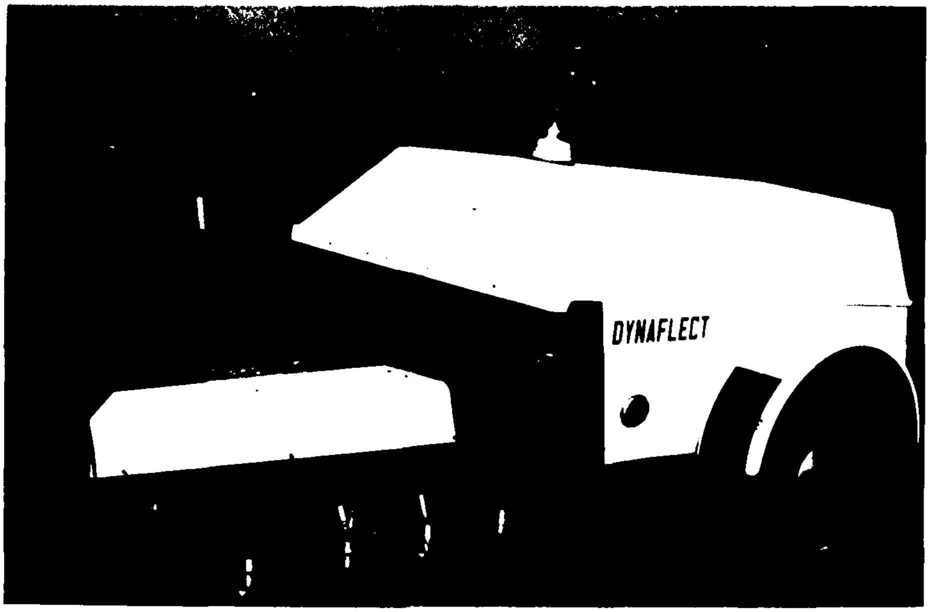

Figure 2. Dynaflect

Two types of signal conditioning and recording devices are available with the Dynaflect. With the standard control unit, the frequency (8 Hz) is monitored on a meter, but the deflections from each of the five sensors must be hand-recorded from a single meter by switching an indicator to each of five positions (Figure 3). The optional device is a digital control system (Figure 4), which has a digital display for each of the five sensors as well as a meter for monitoring frequency. A thermal printer can be attached to the optional recorder that will record each of the five deflections and a test number.

FALLING WEIGHT DEFLECTOMETER

The FWD (Figure 5) is a relatively new NDT device, particularly to the United States. Extensive research has been performed with the FWD in Europe by different researchers.*,** Basically, a mass (Figure 6)

* A. Bohn et al., "Danish Experiments with the French Falling Weight Deflectometer," Proceedings of the Third International Conference on Structural Design of Asphalt Pavements, Vol 1, London, 1972.

** A. Claessen et al., "Pavement Evaluation with the Falling Weight Deflectometer," Proceedings of the Association of Asphalt Paving Technologists, Vol 45, 1975.

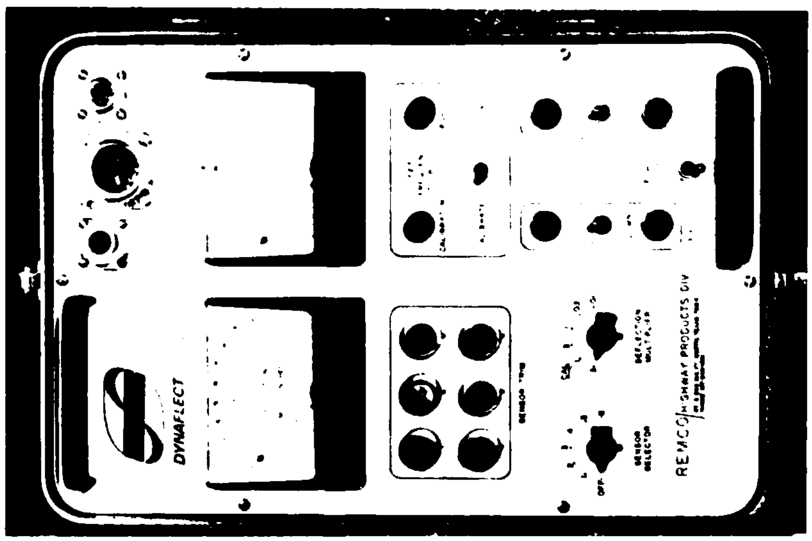

Figure 3. Dynaflect standard control unit

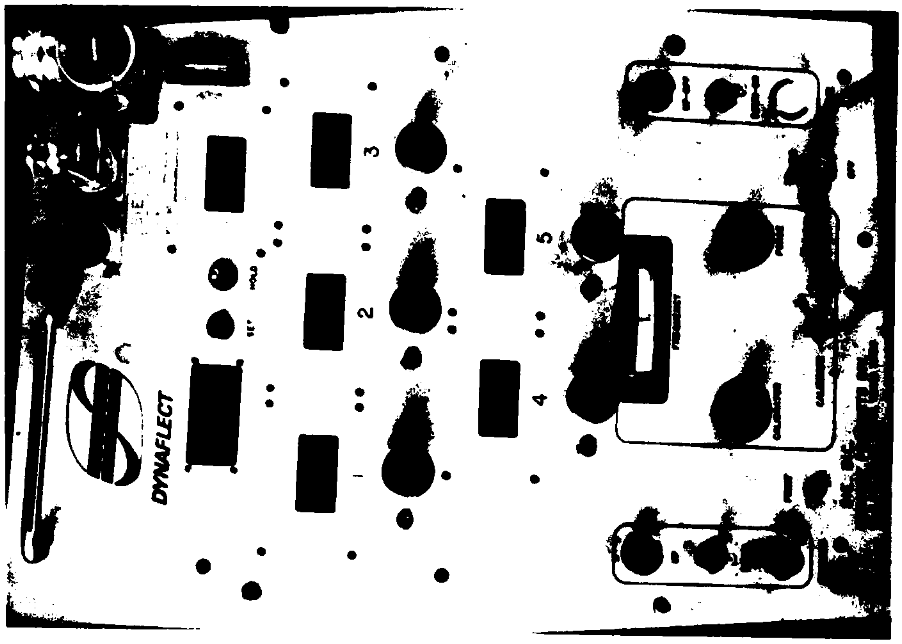

Figure 4. Dynaflect digital control unit

Figure 5. Overall view of the FWD

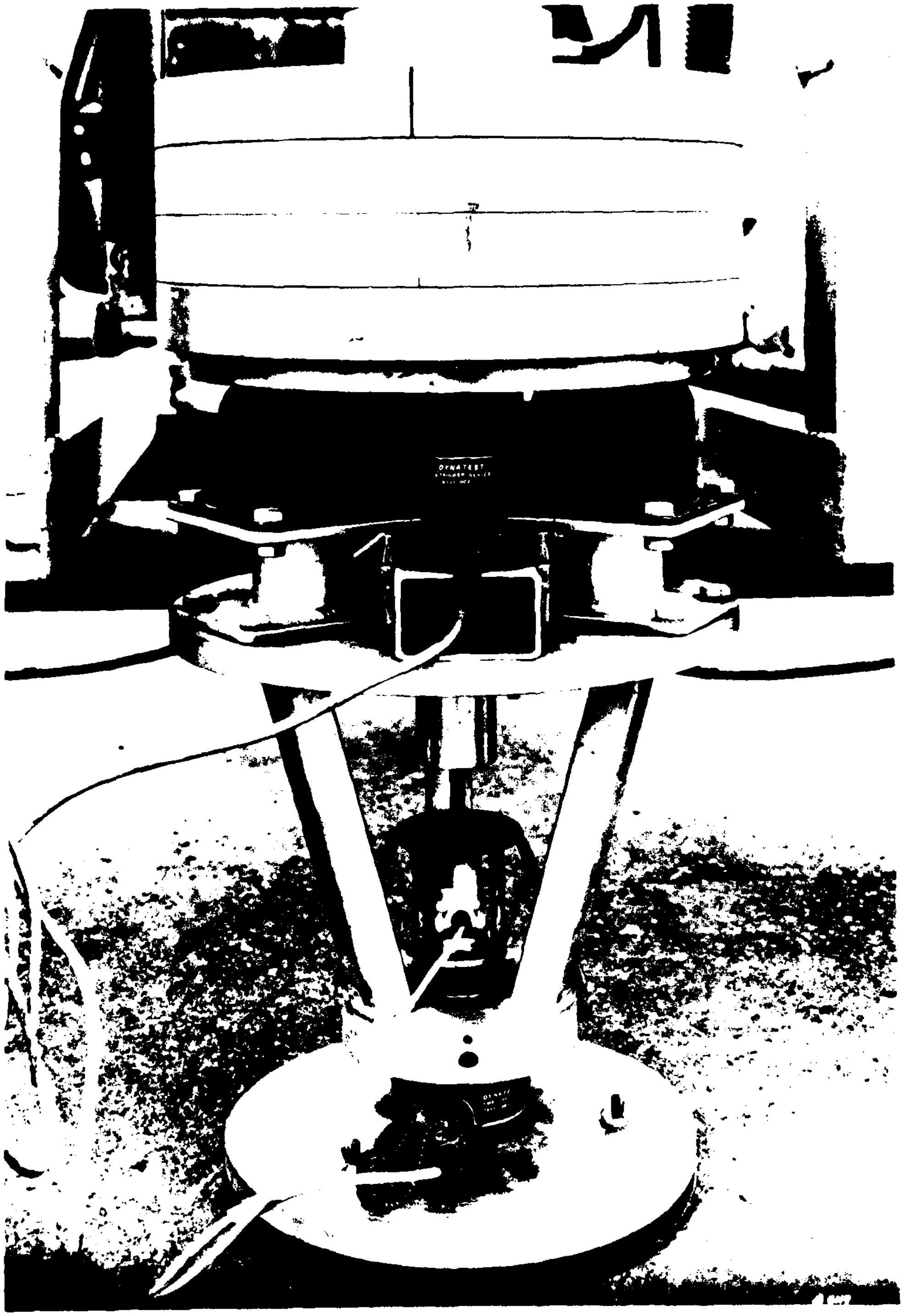

Figure 6. Closeup of the FWD

weighing 330.7 lb (150 kg) is dropped on a set of rubber cushions, and the resulting force and deflection are measured by load cells and velocity transducers. The drop height can be varied from 0 to 15.7 in. (40 cm) to produce a force from 0 to 13,488 lb (60 kN). The device is trailer-mounted, having a total weight of 1,200 lb (544 kg). The load is transmitted to the pavement through an 11.8-in. (30-cm) plate that has a rubber cushion attached. The signal conditioning equipment (Figure 7) displays the resulting pressure in kilopascals and the maximum peak displacement in micrometres. As many as three displacement sensors may be recorded. Two people are required for an efficient operation.

MODEL 400 ROAD RATER

The Road Raters are manufactured by Foundation Mechanics, Inc., El Segundo, California. The Model 400 is an electrohydraulic loading device mounted on the front of a truck or van (Figure 8). The control display console (Figure 9) contains all the controls and readout meters required to operate the hydraulic system and read the data. Power for this unit is from the vehicle's 12-volt electrical system.

The mass weight of 160 lb (73 kg) and the actuator (hydraulic ram) are mounted with the rod end upward. (The opposite is true for the 16-kip (7.3-metric ton) vibrator.) The actuator is capable of a 0.3-in. (7.6-mm) peak-to-peak stroke and produces a vibratory load ranging from 0 to 800 lb (3558 N). The dynamic load is transferred to the pavement surface through two 7- by 4-in. (17.8- by 10.2-cm) rectangular steel pads, which are spaced 6 in. (15.2 cm) apart (10 in. (25.4 cm) center-to-center). The static weight of the Model 400 Road Rater can be varied through hydraulic lines that are separated from those used for the oscillation to system pressure. Figure 10 shows the relationship of static load versus system pressure. Normal pressure for the Model 400 is 600 psi (421,860 kg/m^2). Pavement deflection is monitored with four velocity sensors. One is located between the two steel pads. The others are equally spaced at 1-ft (30.5-cm) intervals away from the first one. Variation of force and frequency is provided through a four-way servo valve, which allows flow to either chamber of the vibrator

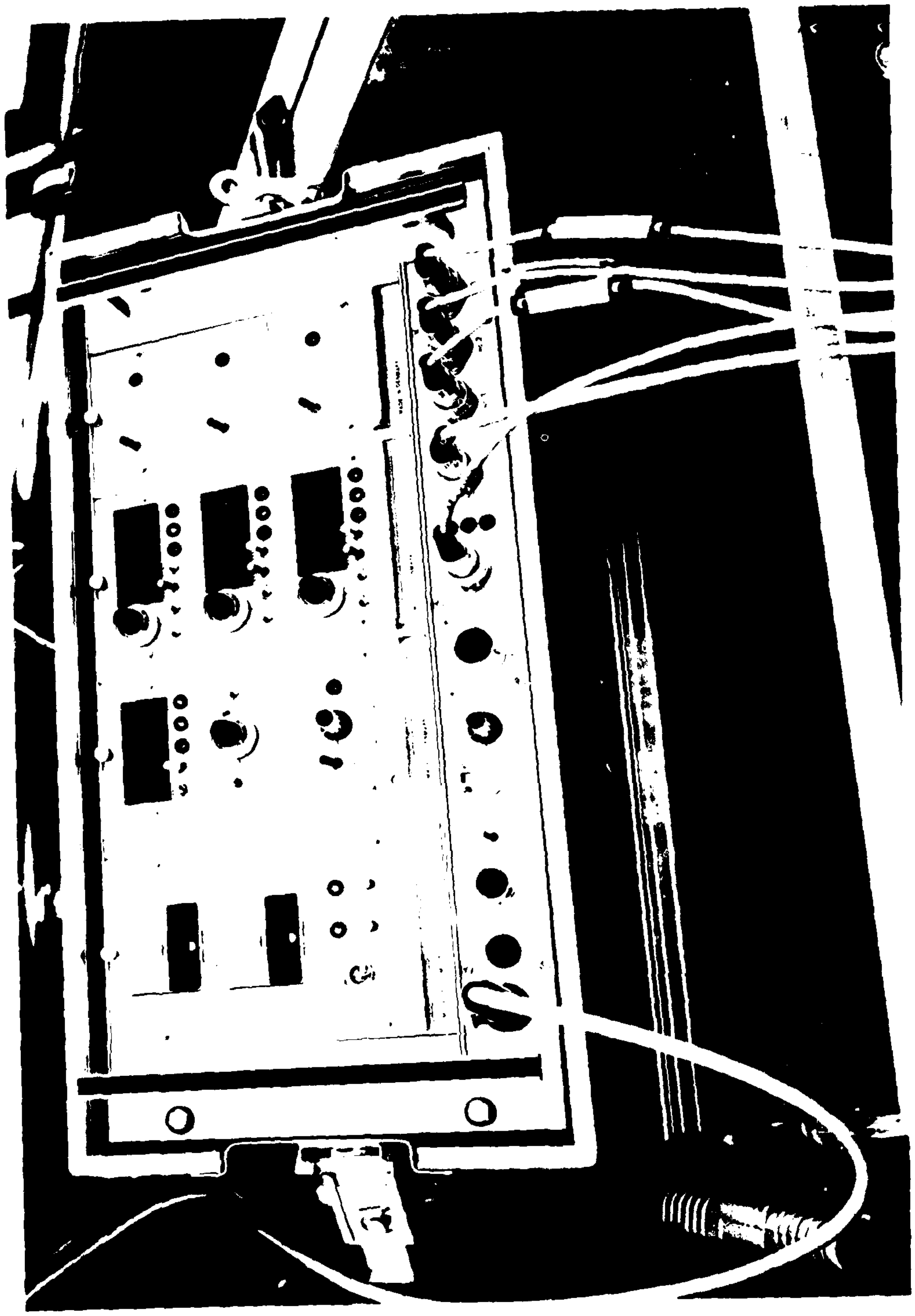

Figure 7. FWD signal conditioning unit

Figure 8. Model 400 Road Rater

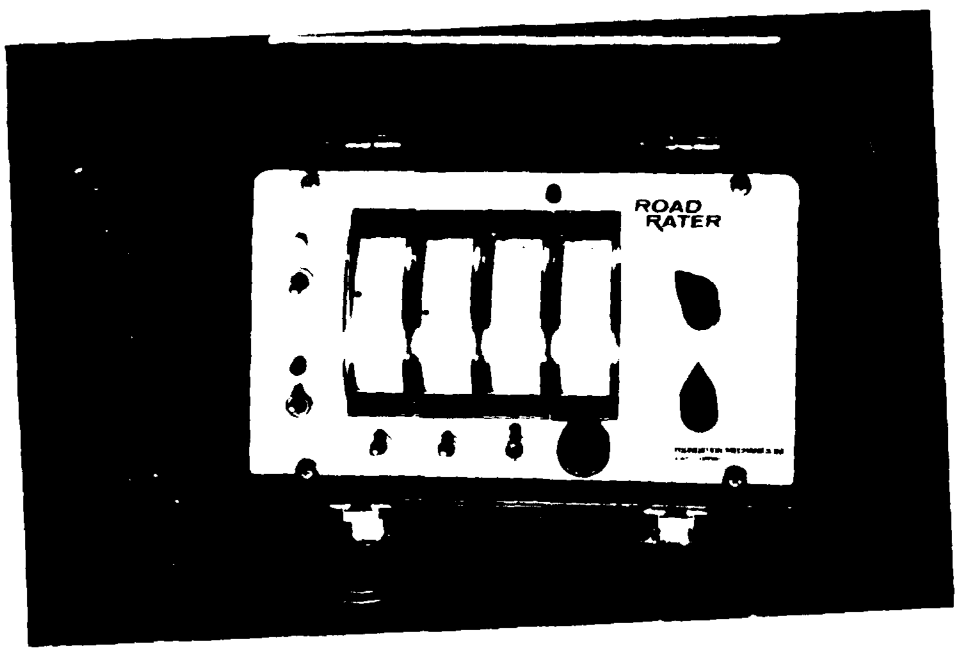

Figure 9. Road Rater readout unit

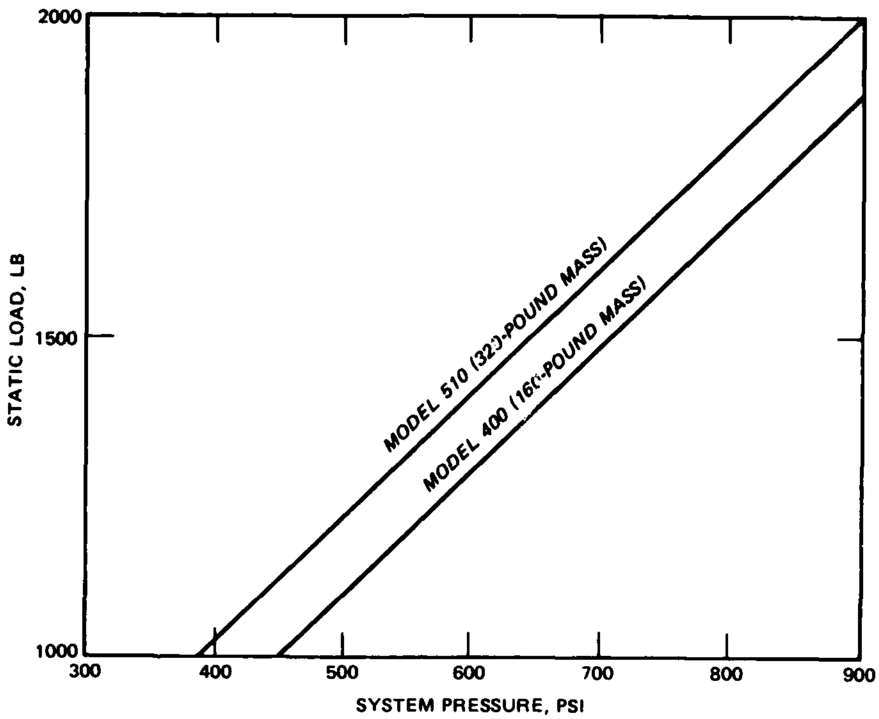

Figure 10. Static load versus system pressure for Models 400 and 510 Road Raters (1 psi = 703 kg/m^2; 1 lb_m = 0.45 kg)

actuator in direct proportion to an oscillating electrical current applied to a torque motor within the valve.

Force and deflections are measured as percentages of full-scale readings on the scales of the control display console (Figure 9). A range switch selects the range value of the displacement readout meters. For example, when the range switch is set at "1," all meters will read displacement as a percentage of 0.001 in. (0.025 mm). Range switches may be set at 1, 2, 3, 5, 10, and 20. Frequency is controlled by a five-position rotary switch, which provides for oscillation at 10, 20, 25, 30, and 40 Hz.

The Model 400 Road Rater has no load cells. Force indicated on the display console is the theoretical calculated force that is based on the sinusoidal oscillation of the mass (acceleration is the second

derivative of the displacement equation for sinusoidal motion). The dynamic force can be calculated from the following equation:

$$F = m\omega^2 x$$

where

F = dynamic force coincident with deflection

m = mass of the vibrator

ω = angular frequency

x = dynamic deflections

For a frequency of 20 Hz and a mass displacement of 0.10 in. (2.54 mm), the force is

$$F = \frac{160 \text{ lb}}{32.2 \text{ ft/sec}^2} \times \left(20 \text{ cycles/sec} \times \frac{2\pi \text{Rad}}{\text{cycle}}\right)^2 \times 0.10 \text{ in.} \times \frac{1 \text{ ft}}{12 \text{ in.}}$$

$$F = 654 \text{ lb peak to peak (2909 N)}$$

MODEL 510 ROAD RATER

The Model 510 is basically the same device as the Model 400 Road Rater with three major exceptions. First, the Model 510 is housed in a 5- by 6-ft (1.5- by 1.8-m) two-wheeled trailer (Figure 11). The mass weighs 320 lb (145 kg) compared with 160 lb (73 kg) for the Model 400 Road Rater. Last, the electrical power is supplied by a self-contained 12-volt direct current (d-c) electrical system.

As with the Model 400, the static weight of the Model 510 is dependent on the system pressure (Figure 10). Normal pressure for the Model 510 is 575 ±25 psi (404,283 ±17,578 kg/m^2) for a static weight of 1,350 lb (6.12 kg). The dynamic force is also calculated the same as with the Model 400. Figure 12 shows a relationship for this force versus the frequency and mass displacement.

The controls for the Model 510 (Figure 9) can be operated from the driver's seat of the towing vehicle. One man can operate this

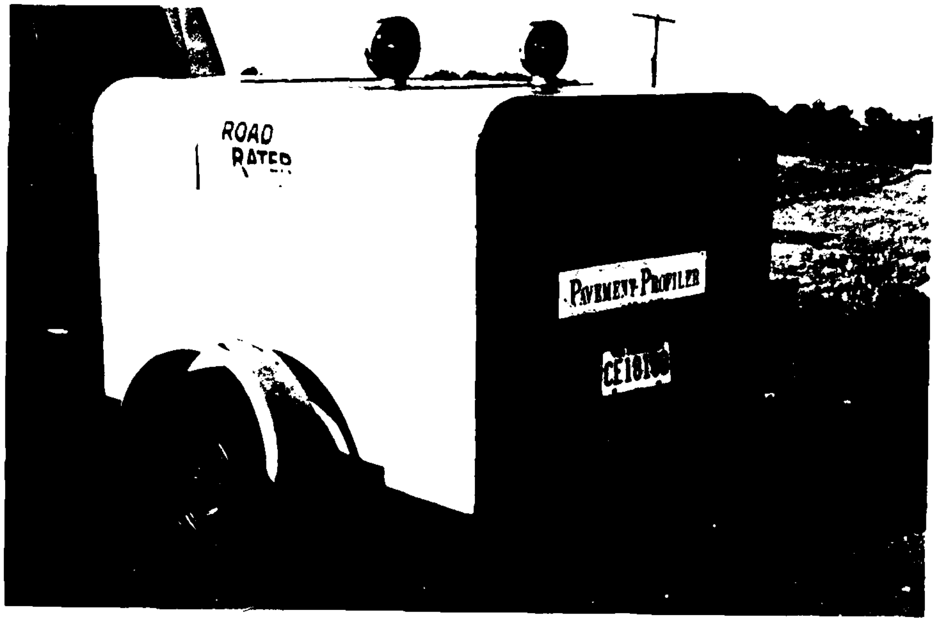

Figure 11. Model 510 Road Rater

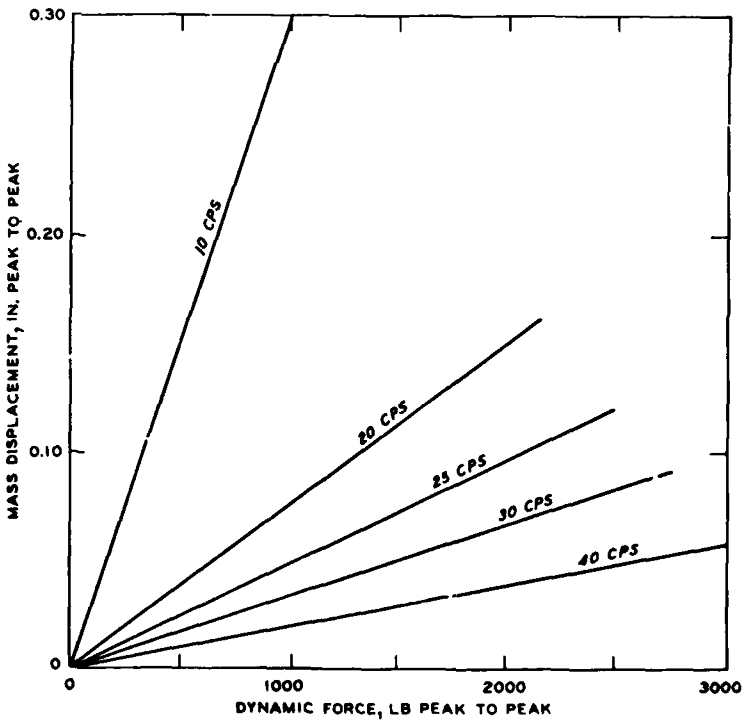

Figure 12. Mass displacement versus dynamic force for the Model 510 Road Rater (1 in. = 2.54 cm; 1 lb_f = 4.448 N)

device, but two would be more efficient by having one man drive, operate the controls, and read out the data while the other records.

MODEL 2008 ROAD RATER

As with the Model 510, the Model 2008 Road Rater is a trailer-mounted, electrohydraulic vibrator (Figure 13). Also, like the WES 16-kip vibrator, the Model 2008 has a variable force and frequency capability. Furthermore, the Model 2008 has a digital control unit (Figure 14) with a light-emitting diode (LED) display that by activating the proper switch, the force, frequency, or any one of four of the velocity sensors can be monitored during a test. Data for the Model 2008 are recorded on a thermal printer located in the control console. The test label number (0-9999), frequency, force, and four deflections are recorded either on the operator's command or during the automatic mode. Under the automatic mode, the operator activates the mode by pushing one switch. The mass is lowered to the pavement, the vibrator is turned on, vibrations are generated at a preselected force and frequency, data are recorded by the printer, and the vibrator is turned off and raised from the pavement.

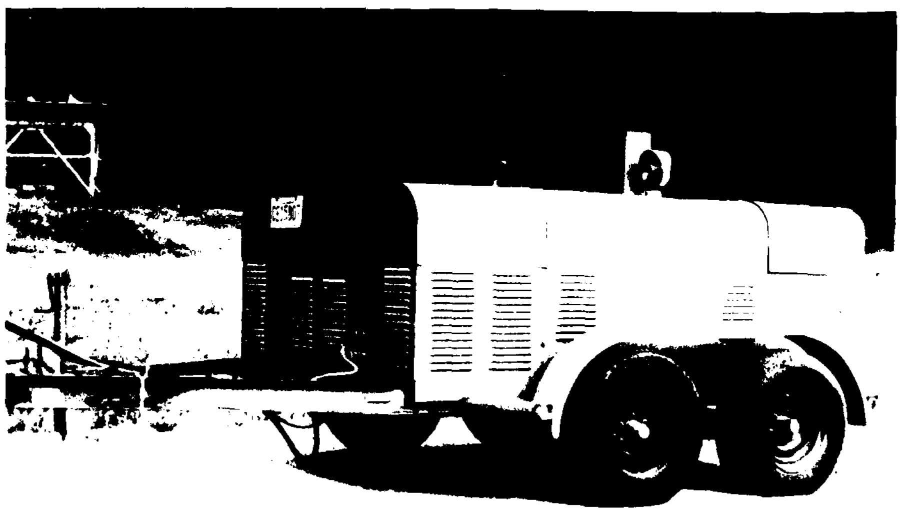

Figure 13. Model 2008 Road Rater

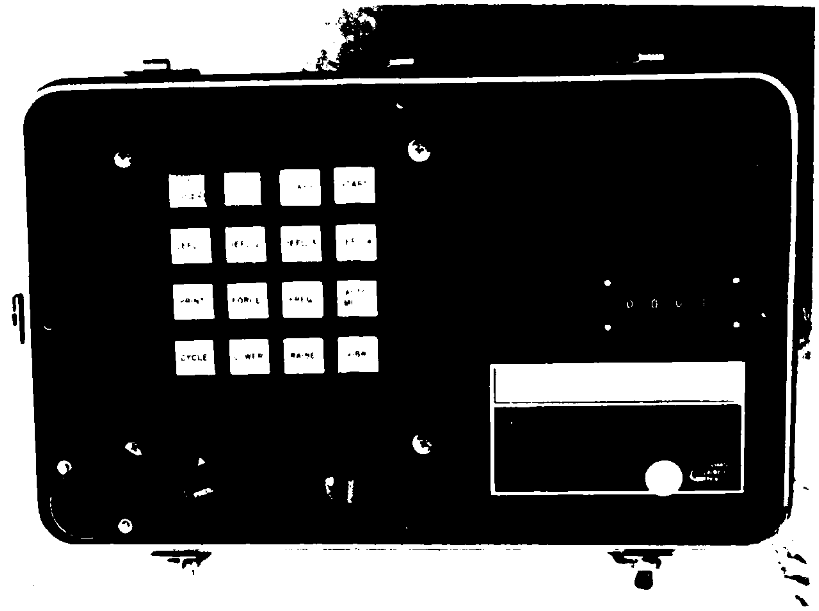

Figure 14. Model 2008 Road Rater control unit

The Model 2008 has a self-contained power supply. The gasoline engine supports the hydraulic and electrical systems of the device. The mass of the Model 2008 is 4000 lb (1814 kg). During this research effort, the 4000-lb (1814-kg) mass was lowered to the pavement and disconnected from the trailer. A recent modification was made that allows the use of the trailer for the reaction force similar to the Model 510.

The Model 2008 Road Rater has three load cells to monitor the force. The loads are summed for a total force output. Deflection is monitored by four velocity sensors. The first is located in the center of the 18-in.- (45.7-cm-) diam load plate. The sensor actually rests on the pavement in a hole in the load plate. The other sensors are spaced at 1-ft (30.5-cm) intervals to the rear of the trailer from the first sensor.

WES 16-KIP VIBRATOR

Part of the description of the WES 16-kip vibrator given by Green and Hall* is repeated here for the convenience of the reader. The 16-kip vibrator, which is an experimental prototype model, operates electrohydraulically and is housed in a 36-ft (11-m) semitrailer that contains supporting power supplies and automatic data recording systems. The vibrator mass assembly consists of an electrohydraulic actuator surrounded by a 16,000-lb (7,257-kg) lead-filled steel box. The actuator uses up to a 2-in. (5.1-cm) double-amplitude stroke to produce a vibratory load ranging from 0 to 30,000 lb (133.4 kN) peak to peak with a frequency range of 5 to 100 Hz for each load setting. Electric power is supplied by a 25-kw diesel-driven generator set. The hydraulic power unit is diesel-driven and has a pump that can deliver 38 gal/min (143 ℓ/min) at 3,000 psi (2,109,300 kg/m^2).

Major items of electronic equipment are a set of three load cells (BLH Electronic Model U3L1, 20,000-lb (88.9 kN) capacity), which measure the load applied to the pavement; velocity transducers (Mark Product Model L-1-U) located in the 18-in.- (45.7-cm-) diam steel load plate and at points away from the load plate, which are calibrated to measure deflections; a servomechanism, which allows variation of frequency and load; an X-Y recorder, which produces load versus deflection and frequency versus deflection curves; and a printer, which provides data in digital form. Figure 15 shows an overall view of the 16-kip vibrator.

With this equipment, the vibratory load can be varied at constant frequencies, and load versus deflection can be plotted. These load-deflection data are used to compute the dynamic stiffness modulus (DSM) for a pavement structure. Frequency can be varied from approximately 5 to 100 Hz at constant force levels to produce the frequency response of the pavement structure. Also, at any selected load or frequency, a plot of the deflection basin shape can be drawn using data from the velocity

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* Green and Hall, op. cit., p. 1.

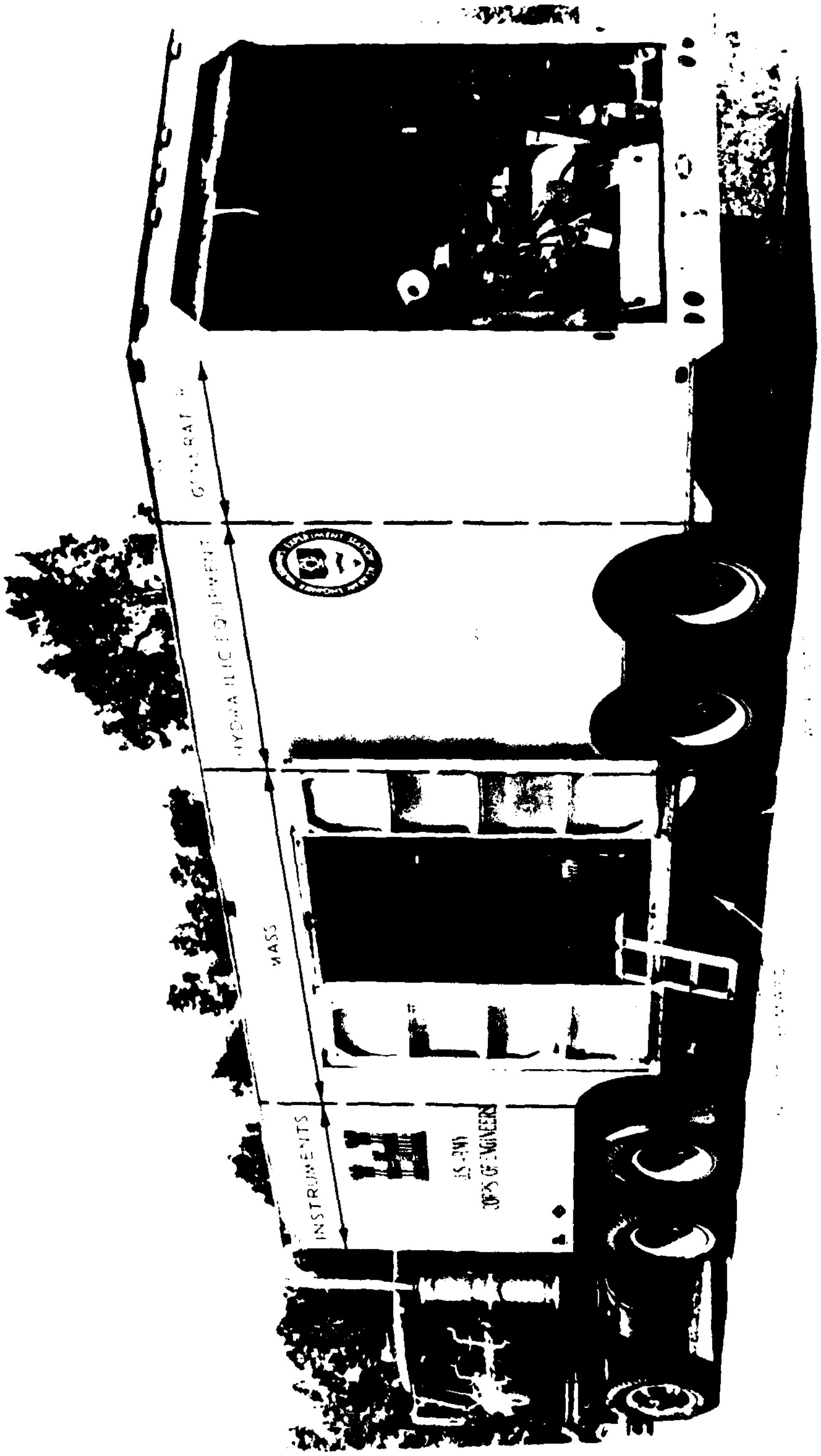

Figure 15. Overall view of the WES 16-kip vibrator

transducers. The WES 16-kip vibrator can also be used to measure the velocity of shear waves propagated through various pavement layers. Wavelengths can be measured by manually moving a velocity transducer on the ground, observing the results on an oscilloscope, and manually recording the results. This procedure is repeated for different frequencies of loading, and the wave velocity is obtained by multiplying the frequency times the corresponding wavelengths.

EVALUATION RESULTS

OPERATIONAL CHARACTERISTICS

EASE

In evaluating each device for ease of operation, one important evaluation criterion was the operator training required before operation. Another criterion was the amount of physical labor required for a test. Both of these criteria were evaluated equally. The Benkelman Beam is the simplest device of all, but in terms of operator training, it requires probably as much or more than any of the other devices. The Benkelman test is a cumbersome test. A truck must be positioned and the arm placed between the dual tires, the gages zeroed, the truck moved away, the gage read and recorded, and then the equipment picked up and moved to the next test location.

The Dynaflect requires about one hour of operator training. The velocity pickups must be calibrated, then attached to the device. After the initial warmup and calibration, the Dynaflect is relatively simple to operate. There were two different models evaluated under this project. One had a digital control unit, while the other had a standard analog control. The digital system had an optional printer system, which was not evaluated. The digital unit displays the results from all four or five velocity sensors. The standard control requires changing a dial so that each sensor can be monitored using only one meter. To conduct a test, the vibratory wheels are lowered to the test position. Another switch is tripped to lower the velocity pickups, the displays are allowed to stabilize, and the values recorded. The pickups are then raised. If the test interval is short enough and the pavement is smooth, the vibrator is left running with the wheels down. When the next position is reached, only the pickups have to be lowered. After the initial setup, and if the vibrator wheels can be left down, the Dynaflect with the digital control is the easiest to operate of all devices evaluated.

The operational ease of the Models 400 and 510 Road Raters will be discussed together since they are so similar. These vibrators

require very little calibration. The manufacturer recommends calibration once a month. The operation then consists of initially removing a locking mechanism that holds the vibrator in the "up" position. Then, for a series of tests, the vibrator is lowered to the pavement and activated at the desired frequency, the force output is checked, and a switch is engaged to allow reading all four velocity sensors. The vibrator is then raised and the vehicle moved to the next location. In comparing the two vibrators, the Model 400 allows easier operation than the Model 510 since the operator does not have to maneuver a trailer. The Model 400 with a mirror positioned correctly allows the driver to easily position the device over a preselected test point. All other devices require another person to guide over a preselected point.

The Model 2008 Road Rater has a digital control unit that also allows for simple operation. On a normal setup, the support arm for the velocity gages and the gages must be installed and the pressure in the air bags checked. A set of locking bars are removed so that the mass can be lowered by the hydraulic lift cylinders, and the device is then ready for operation. In the automatic cycle setting, one switch causes the vibrator to conduct the test, record the data, and prepare to move to the next location.

SPEED

The criterion for evaluating speed was established as the time required to conduct one test, move 100 ft (30.5 m), and then be prepared to begin the second test. Speed of operation is a function of manpower requirements. For this evaluation, the optimum case was selected to evaluate speed. Hence, if a device can be operated by one person but two are more efficient, speed was evaluated with two operators. The Road Raters have the capability of operating at varying loads and frequencies. The load of the FWD can be varied by changing the drop height. For evaluation of operation speed, only one test load and one frequency were considered.

According to the results of the speed evaluation given in Table 2, the Benkelman beam and the FWD rank first and second, respectively, in

Table 2

Speed of Operation

Device	Daily Set-Up/Calibration Time, *min*	Time Required per Test *min*
Benkelman Beam	10	3-1/4
Dynaflect		
Standard Control Unit	20	1-1/4
Digital Control Unit	20	3/4
FWD	20	1-1/2*
Model 400 Road Rater	15	1
Model 510 Road Rater	15	1
Model 2008 Road Rater	15	1
WES 16-kip Vibrator	60	1-1/2

* Estimated (no production-type tests were conducted).

consuming more time per test than the other candidate devices. The FWD time could be reduced if the velocity sensors could be mechanically placed rather than hand placed.

MANPOWER REQUIREMENTS

Table 3 lists the manpower requirements for each device. Each device that requires recording of the data by hand is more efficiently operated by one additional person. Those devices with automatic recording (Dynaflect and Model 2008 Road Rater) do not require the additional person.

COSTS

INITIAL

Table 4 presents the initial costs based on manufacturers' 1979 prices. Note that the Road Rater is listed in this table as the Model 400A. After completion of the evaluation tests on these devices, it was learned that neither the Model 510 nor the Model 400 were any longer in production. Difficulties with the front mounting of the Model 400

Table 3

Manpower Requirements

Device	Minimum No.	Optimum No.
Benkelman Beam	2	2
Dynaflect		
Standard Control Unit	1	2
Digital Control Unit	1	1*
FWD	1	2
Model 400 Road Rater	1	2
Model 510 Road Rater	1	2
Model 2008 Road Rater	1	1
WES 16-kip vibrator	3	4

* With printer.

Table 4

Equipment Costs

Device	Cost
Benkelman Beam	$ 666
Dynaflect	
With Standard Control Unit	16,000
With Digital Control Unit	19,333
FWD (Hydraulic lift, measures load and three deflections)	28,000
Model 400A Road Rater (does not include vehicle)	22,000
Model 2008 Road Rater	40,000

resulted in a unit mounted in the rear of the van, hence the Model 400A. The mass of the Model 400A is 320 lb (145 kg), the same as the Model 510. A Road Rater Model 2000 is also manufactured with a 2,000-lb (907-kg) mass at a cost of $36,000. This model was not tested during this study but will deliver one-half the force of the Model 2008.

OPERATING

During this study, the devices were not operated for a long enough period to establish a precise operating expense comparison. Observations made during this study and during other projects where candidate devices were used will be discussed.

The primary cost for operating all the candidate devices will be attributed to the cost of labor required for operation, assuming that vehicles are available to tow the trailer-mounted rigs (Dynaflect, and Models 510 and 2008 Road Raters) and that there is a truck for the Benkelman Beam. Fuel costs would be approximately the same for all candidate devices. The Models 510 and 2008 would require some additional fuel for their power supply engines, but these engines only use about 5 gal (19 ℓ) in an 8-hr day. This cost would be minimal when an operator cost of $100 per day is estimated.

Maintenance costs would be nil for the Benkelman Beam. The Dynaflect seems to require little maintenance, particularly if it is not abused. Maintenance was required on two of the three Dynaflects we observed. One case was caused by not operating according to the manufacturer's recommendations (i.e., driving too fast with the wheels down in the vibratory mode). In the other case, maintenance was required to the digital system, probably because of lack of use for long periods of time. In both cases, the devices were corrected in the field with minimum delays.

The Models 400 and 510 Road Raters require very little maintenance. Maintenance costs are insignificant if a few preventive maintenance steps are followed. The Model 2008 Road Rater is relatively new. Effects of age and continued use cannot be evaluated. The FWD should not require any maintenance costs, since it is a very simple apparatus.

Therefore, because maintenance requirements are few and fuel costs are very nearly equal, the operator cost will govern the operating cost for all devices.

TRANSPORTABILITY BY CARGO AIRCRAFT

The problems associated with transporting the WES 16-kip vibrator overseas led to the evaluation parameter of transportability. Since this large device can only be carried by the C-5 aircraft, any commercial transportation is eliminated. In the evaluation of this parameter, it was found that the Benkelman Beam is completely transportable by practically any means. Since the Model 400 Road Rater has to be permanently attached, it has to be evaluated with the truck attached, which also makes it the largest of the candidates.

In evaluating the trailer devices, it was found that if the airport is serviced by a major cargo carrier, all can be transported. If the airport does not have a cargo carrier, it will depend on the local situation as to the transportability. Different carriers have different operating procedures, and airports have different loading equipment. Generally, ranking of the trailer devices in terms of their gross weight would be in the order of the FWD, the Dynaflect, the Model 510, and the Model 2008. However, according to air cargo personnel at several airports, each of these devices would require the same aircraft. The size of the van on which the Model 400 Road Rater was mounted would restrict this device to some extent (i.e., would not fit in the cargo area of a B-727). Therefore, in rating air transportability, the Benkelman Beam is first, the Model 400 Road Rater is last, and all the others are grouped between these two devices.

ACCURACY AND REPRODUCIBILITY OF MEASUREMENTS

DEFLECTION

The accuracy of the deflection measurement of the Benkelman Beam was checked by placing premeasured calibration shims under the beam toe and recording the readings. A wide range of deflections was selected

since the static deflections measured in the Benkelman Beam tests are generally larger than the dynamic deflections under the vibrators. Table 5 presents the results of these tests.

Table 5

Accuracy of Benkelman Beam Deflection Measurements

Known Input in.	Measured Deflection in.	Percent Error
0.0640	0.066	3.1
0.0372	0.036	-3.3
0.0270	0.0279	3.3
0.0220	0.0238	8.2
0.0140	0.0160	14.3
0.0080	0.0083	3.8
0.0190	0.0200	5.3
0.0050	0.0047	-6.0
0.0030	0.0036	20.0
0.0020	0.0024	20.0
	Mean Percent Error	8.7

Note: 1 in. = 2.54 cm.

To determine the accuracy of deflection measurements of the vibrators, a calibrated shake table was used. Each transducer was vibrated at known deflections on the shake table, and the output signal from each transducer was recorded on the particular device's data acquisition system. The calibration of the shake table was based on an MB Model 1241 vibration transducer, which was precision-calibrated by MB Electronics.

In Table 6, the results of the tests on the five Dynaflect sensors are tabulated. Each sensor was vibrated at six different known deflections ranging from 0.5 to 20 mils (0.012 to 0.51 mm), and the measured Dynaflect deflection recorded. The percent error in each Dynaflect reading was also computed (Table 6).

Table 6

Accuracy Test of Dynaflect Velocity Sensors

Known Input in.	Velocity Sensors No. 1 Displacement in.		No. 2 Displacement in.		No. 3 Displacement in.		No. 4 Displacement in.		No. 5 Displacement in.		Mean Percent Error
	Displacement in.	Percent Error	Displacement in.	Percent Error	Displacement in.	Percent Error	Displacement in.	Percent Error	Displacement in.	Percent Error	
0.0200	0.0204	2.0	0.0207	3.5	0.0207	3.5	0.0207	3.5	0.0213	6.5	3.8
0.0100	0.0105	5.0	0.0111	11.0	0.0108	8.0	0.0111	11.0	0.0111	11.0	9.2
0.0050	0.0051	2.0	0.0051	2.0	0.0052	4.0	0.0052	4.0	0.0053	6.0	3.6
0.0020	0.00207	3.5	0.00207	3.5	0.00213	6.5	0.00222	11.0	0.00225	12.5	7.4
0.0010	0.00099	-1.0	0.00105	5.0	0.00102	2.0	0.00099	-1.0	0.00105	5.0	2.8
0.0005	0.00046	-8.0	0.00047	-6.0	0.00046	-8.0	0.00049	-2.0	0.00046	-8.0	-6.4
Mean percent error		3.6		5.2		5.3		5.4		8.2	

Note: $\text{Percent error} = \frac{\text{Dynaflect value} - \text{known input}}{\text{known input}} \times 100$.

1 in. = 2.54 cm.

Deflections were measured with the Model 510 Road Rater for eight known input deflections at frequencies of 10, 20, 25, 30, and 40 Hz (Table 7). The mean percent error varied with frequency from -3.3 percent at 40 Hz to -26 percent at 10 Hz and with known deflection from +1.4 percent at 0.00140 in. (0.035 mm) to -16 percent at 0.00040 in. (0.01 mm) (smallest known input). The mean percent error was greater than 10 percent for only measurements at 10 Hz and known input deflections of less than 0.00080 in. (0.02 mm) peak to peak. Velocity transducers of the Model 510 Road Rater and the WES 16-kip vibrator are comparable in the accuracy of their measurements. Velocity sensors of the Model 400 Road Rater are the same as those of the Model 510. The control box is also the same; therefore, the accuracy will be assumed similar for both devices.

The accuracy data for the velocity sensors of the Model 2008 Road Rater are summarized in Table 8. Note that the deflections presented are the average for frequencies of 5, 8, 15, 25, and 50 Hz and the percent errors presented in the lower part of the table are averaged for the six known deflections ranging from 0.5 to 20 mils (0.012 to 0.51 mm). Again, this is very similar to the accuracy for the WES 16-kip vibrator in that the error is greater at 5 Hz and becomes more consistent at the other frequencies.

Accuracy tests for the FWD consisted of placing the velocity sensor of the WES 16-kip vibrator beside the sensor of the FWD and comparing results (Figure 16). This check is not as precise as the use of the calibrated shake table; therefore, the differences in method should be considered when comparing the FWD accuracy with the accuracy of the other devices. This expedient method was used due to constraints of time and funding.

FORCE AND FREQUENCY

To test the accuracy of force for each device, load cells were used to measure the output. Frequencies were counted electronically from the load cell signal in the form of periods.

To measure the dynamic force output from the Dynaflect, a BLH

Table 7

Accuracy Test of Model 510 Road Rater Velocity Sensor

Known Input in.	Frequency, Hz: 10 Mean, in.	10 Percent Error	20 Mean, in.	20 Percent Error	25 Mean, in.	25 Percent Error	30 Mean, in.	30 Percent Error	40 Mean, in.	40 Percent Error	Mean Percent Error
0.00040	0.00012	-70	0.00037	-7.5	0.00037	- 7.5	0.00040	0	0.00041	+ 2.5	17.5
0.00080	0.00044	-45	0.00077	-3.8	0.00076	- 5.0	0.00081	+1.2	0.00083	+ 3.8	11.8
0.00120	0.00090	-25	0.00126	+5.00	0.00122	+ 1.67	0.00128	+1.67	0.00132	+10.0	8.7
0.00140	0.00114	-18.6	0.00148	+5.70	0.00142	+ 1.43	0.00152	+8.57	0.00154	+10.0	8.9
0.00160	0.00136	-15.0	0.00170	+6.25	0.00147	- 8.12	0.00156	-2.50	0.00162	+ 1.25	6.6
0.00200	0.00178	-11.0	0.00192	-4.00	0.00186	- 7.00	0.00195	-2.50	0.00189	- 1.00	5.1
0.00300	0.00255	-15.0	0.00280	-6.67	0.00270	-10.0	0.00285	-5.00	0.00290	- 3.33	8.0
0.00600	0.00570	- 5.00	0.00620	+[illegible].33	0.00580	- 3.33	0.00600	0	0.00620	+ 3.33	3.0
Mean Percent Error		26		5.3		5.5		2.7		4.4	

Note: Percent Error = $\frac{\text{measured input - known input}}{\text{known input}} \times 100$.
Deflections are peak-to-peak values.
1 in. = 2.54 cm.

Table 8

Accuracy Test of Model 2008 Road Rater Velocity Sensors

Known Input in.	Velocity Sensors: No. 1 Mean* in.	No. 1 Percent Error	No. 2 Mean* in.	No. 2 Percent Error	No. 3 Mean* in.	No. 3 Percent Error	No. 4 Mean* in.	No. 4 Percent Error
0.0200	0.01832	-8.4	0.0180	-10.0	0.02240	12.0	0.01744	-12.8
0.0100	0.00919	-8.1	0.00885	-11.5	0.00984	-2.1	0.00876	-12.4
0.0050	0.00461	-7.6	0.00451	-9.8	0.00467	-1.8	0.00443	-11.6
0.0020	0.00184	-8.0	0.00181	-9.5	0.00188	-6.0	0.00181	-9.5
0.0010	0.00089	-11.0	0.00090	-10.0	0.00094	-6.0	0.00094	-6.0
0.0005	0.00047	-6.0	0.00046	-8.0	0.00048	-4.0	0.00049	-2.0
Mean Percent Error for Each Sensor		8.2		9.8		5.3		9.1
Hz	**Mean Percent Error as a Function of Frequency for Each of the Above Known Displacements**							
5		-18.4		-19.0		-22.4		-17.1
8		-3.7		-5.3		6.6		-3.6
15		-5.4		-8.9		6.0		-7.0
25		-7.7		-7.7		-2.7		-9.7
50		-5.8		-8.2		6.6		-9.4

Note: Percent error = $\frac{\text{RR2008 value - known input}}{\text{known input}} \times 100$.

1 in. = 2.54 cm.

* Mean displacements are for frequencies of 5, 8, 15, 25, and 50 Hz.

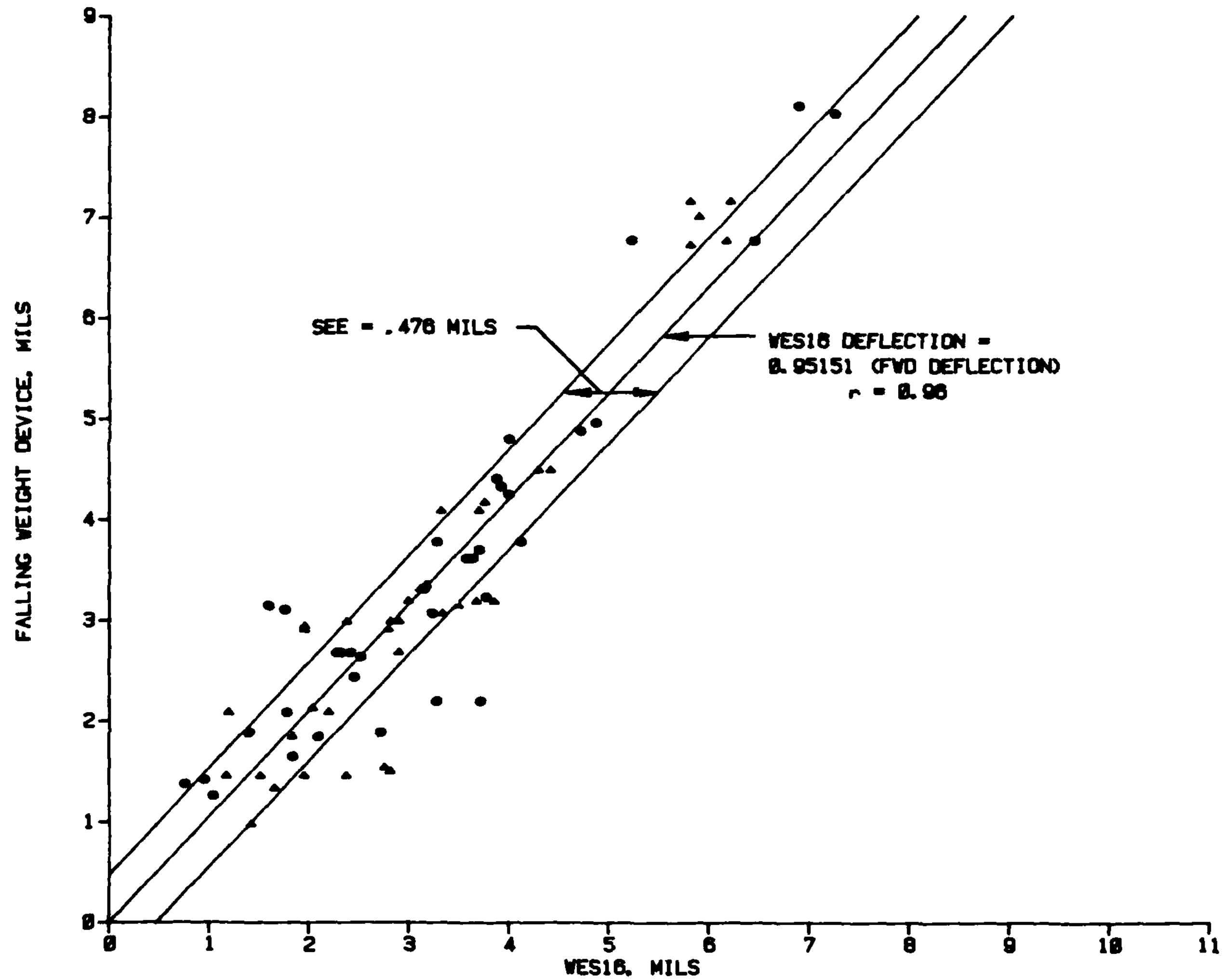

Figure 16. Comparison of FWD and WES 16-kip vibrator deflection measurements (1 mil = 25.4 microns)

load cell was placed under each of the steel loading wheels, and the results were tabulated (Table 9). Since the Dynaflect force is a computed value and is assumed to be constant, tests were conducted to see if this force actually remained constant with variations in deflection of the loaded surface. Both rigid and flexible pavements were tested to determine if the high deflections on flexible and lower values for rigid might influence the force output. Changing the amount of deflection did change the error in load. The frequency dial on the Dynaflect control is divided by tick marks with 8 Hz being in the center of the dial. Frequency was measured with the frequency adjusted so that the dial registered one mark above and again at one mark below 8 Hz. Table 9 also presents these test results.

The impulse load input to the ground surface was measured for the FWD by dropping the weight on three BLH load cells sandwiched between two 18-in.- (45.7-cm-) diam steel plates. Plates were firmly bolted to the load cells. The FWD plate was placed on top of this sandwiched construction. Measured loads were determined from oscillograph records of the load signal. Table 10 summarizes the results of these tests. As noted, the measured force was consistently higher for the different drop heights.

For the Model 510 Road Rater, the same sandwiched load cell apparatus was used to measure the load. Table 11 shows the comparisons of calculated to measured peak-to-peak loads. Loads were compared at frequencies of 10, 20, 25, 30, and 40 Hz. Calculated loads were consistently higher than measured loads but tend to agree best at high loads and higher frequencies. The worst agreement was at a measured load of 1100 lb (4893 N) and 25 Hz where the calculated load minus the measured load expressed as a percentage of the measured load was -57.3 percent. The best agreement was also at 25 Hz and measured load of 2075 lb (9230 N) where the percent difference, computed as above, was -12.3 percent.

Again, the Model 400 was not tested, but being so similar to the Model 510, differences in measured and calculated loads should be similar. Accuracy of frequency was not tested on the Model 510 Road

Table 9

Accuracy Test for Dynaflect Force and Frequency

Dynaflect Frequency	Measured Frequency	Percent Error	Dynaflect Force	Rigid Pavement Measured Force lb	Rigid Pavement Percent Error	Flexible Pavement Measured Force lb	Flexible Pavement Percent Error
8	8.26	-3.1	1000	1044	-4.21	1148	-12.9
8+1*	8.50						
8-1**	7.94						

Note: Percent error = $\frac{\text{Dynaflect value - measured value}}{\text{measured value}}$

1 lb = 4.448 N.

* Indicated frequency of 8 Hz plus 1 gradation on the dial.

** Indicated frequency of 8 Hz minus 1 gradation on the dial.

Table 10

Accuracy Test for FWD Force

FWD Force lb	Measured Force lb	Percent Error
5,640	6,075	-7.2
5,687	5,975	-4.8
11,311	11,810	-4.2
Mean percent error		-5.4

Note: Percent error = $\frac{\text{FWD force - measured force}}{\text{measured force}}$.

1 lb = 4.448 N.

Table 11

Comparisons of Calculated and Measured Loads for the Model 510 Road Rater

Frequency Hz	Scale %	Mass Displacement in.	Calculated Load lb	Measured Load lb	Percent Error $\frac{\text{Cal.} - \text{Meas.}}{\text{Meas.}} \times 100$
10	50	0.150	500	875	-42.8
10	82	0.246	756	1400	-46.0
20	13	0.039	500	845	-40.8
20	25	0.075	1000	1525	-34.4
20	37	0.111	1500	2025	-25.9
20	42	0.126	1675	2150	-22.1
25	8	0.024	470	1100	-57.3
25	16	0.048	1000	1775	-43.7
25	24	0.072	1500	2000	-25.0
25	29	0.087	1820	2075	-12.3
30	6	0.018	350	750	-53.3
30	11	0.033	940	1325	-29.0
30	17	0.051	1500	1875	-20.0
30	22	0.066	2000	2400	-16.7
40	3	0.009	400	612	-34.6
40	7	0.021	1050	1300	-19.2
40	10	0.030	1500	2025	-25.9
40	13	0.039	2000	2900	-31.9
40	15	0.045	2400	3250	-26.1

Note: 1 in. = 2.54 cm; 1 lb = 4.448 N.

Rater, but by counting cycles on oscillograph output, a good agreement in frequency was indicated.

Being a vibrator with a variable frequency and force capability, the Model 2008 Road Rater required much more testing. The force and frequency were varied to check the accuracy. Accuracy checks (Table 12) were made at two force levels of 3,000 (13,445 N) and 5,000 lb (22,241 N) over a frequency range from 5 to 50 Hz. The frequency was generally between 3 and 4 percent higher than the measured frequency, whereas the indicated load was about 4.5 percent lower than the actual measured load. During another test for accuracy, the force signal was filtered with a band pass filter which removed all harmonics that may add to or subtract from the input signal. By filtering the force signal, the percent error was reduced to less than 1 percent (Table 13). The force signal will be presented later to illustrate this error.

FORCE, VELOCITY, AND DEFLECTION SIGNALS

To better understand the parameters inputted to the pavement and the response of the pavement to these parameters, traces of the force, velocity, and deflection are discussed. Figure 17 presents the Dynaflect signals. The sine wave for each parameter is excellent; however, the velocity signal does show some overriding noise. Figure 18 shows the force and velocity for the FWD. Note that the response on the FWD registration equipment records only the first peak. During accuracy testing of the FWD and also on the depth of influence tests to be discussed later, deflections were calculated by measuring with a planimeter the area under the velocity trace. The electronic system used for accuracy tests on the other vibrators required a steady-state signal to integrate velocity for deflection determination.

For the Model 510 Road Rater, only the force signal was recorded. The traces are for loads near the upper limits for frequencies of 10, 20, 25, 30, and 40 Hz (Figure 19). These traces approach a sinusoidal solution. The Model 400 Road Rater was not available for this type testing, but except for magnitude, the shapes will be similar to those of the Model 510.

Table 12

Accuracy Test for Model 2008 Road Rater Force and Frequency
(Measured Force Unfiltered)

RR 2008	3000-lb Force						5000-lb Force					
	Measured						Measured					
Frequency Hz	Period millisec	Frequency Hz	Percent Error	RR2008 Force lb	Measured Force lb	Percent Error	Period millesec	Frequency Hz	Percent Error	RR2008 Force lb	Measured Force lb	Percent Error
5	225.0	4.44	12.6	3097.5	3205.0	-3.4	230.0	4.35	14.9	4925.0	6022.5	-18.2
6	185.5	5.39	11.3	3122.5	3320.9	-6.0	188.5	5.31	13.0	5143.3	5481.9	-6.2
7	155.0	6.45	8.5	3240.0	3098.3	4.5	158.0	6.33	10.6	5100.0	5690.0	-10.4
8	135.0	7.41	8.0	3082.5	2595.3	18.8	136.0	7.35	8.8	5172.5	5735.0	-9.8
9	117.0	8.56	5.1	3087.5	2841.0	8.7	120.0	8.33	8.0	5222.5	5153.9	1.3
10	105.0	9.52	5.0	3110.0	3102.1	0.3	106.5	9.39	6.5	5060.0	5170.9	-2.1
11	95.0	10.53	4.5	3070.0	3236.6	-5.1	96.0	10.42	5.6	5112.5	5122.0	-0.2
12	86.5	11.56	3.8	2985.0	3264.1	-7.6	87.0	11.49	4.4	5082.5	5116.2	-0.7
13	79.5	12.58	3.3	3015.0	3231.6	-6.7	80.4	12.44	4.5	5035.0	5643.4	-10.8
14	73.3	13.64	2.6	3055.0	3350.1	-8.8	75.7	13.21	6.0	5170.0	5612.2	-7.9
15	68.2	14.66	2.3	3000.0	3330.2	-9.9	69.2	14.45	3.8	5157.5	5531.8	-6.8
16	63.7	15.70	1.9	2970.0	3264.6	-9.0	64.5	15.50	3.2	5120.0	5517.6	-7.2
18	56.5	17.70	1.7	2987.5	3383.8	-11.7	56.6	17.67	1.9	5090.0	5315.9	-4.2
20	50.5	19.80	1.0	2972.5	3207.3	-7.3	50.9	19.65	1.8	5020.0	5347.6	-6.1
22	45.5	21.98	0.1	3027.5	3058.2	-1.0	46.0	21.74	1.2	4970.0	5001.4	-0.6
24	41.8	23.92	0.3	3012.5	3074.9	-2.0	42.0	23.81	0.8	4965.0	4727.5	5.0
26	38.5	25.97	0.1	3010.0	3141.6	-4.2	38.8	25.77	0.9	5012.5	4924.0	1.8
28	35.5	28.17	-0.6	3022.5	3104.5	-2.6	36.0	27.78	0.8	5017.5	4865.5	3.1
30	33.0	30.30	-1.0	2972.5	3000.5	-0.9	33.1	30.21	-0.7	5040.0	4819.7	4.6
35	28.5	35.09	-0.3	2995.0	3093.3	-3.2	28.5	35.09	-0.3	5032.5	4997.5	0.7
40	24.8	40.32	-0.8	2915.0	3125.3	-6.7	25.0	40.00	0.0	5010.0	5351.9	-6.4
45	22.1	45.25	-0.6	2952.5	3361.9	-12.2	22.1	45.25	-0.6	3817.5*	4224.3	-9.6
50	19.8	50.50	-1.0	2945.0	3733.7	-21.1	19.4	51.55	-3.0	2876.0*	3294.6	-12.7

Note: Percent error = $\frac{\text{RR2008 value} - \text{measured value}}{\text{measured value}} \times 100$.

1 lb = 4.448 N.

* 5000-lb force could not be obtained at these frequencies.

Table 13

Accuracy Test for Model 2008 Road Rater Force and Frequency (Measured Force Filtered)

RR2008 Frequency Hz	Measured Period millisec	Measured Frequency Hz	Percent Error	RR2008 Force lb	Measured Force lb	Percent Error
5	226.0	4.43	12.9	5187.5	4743.5	9.4
6	186.0	5.38	11.5	5307.5	5078.3	4.5
7	156.6	6.39	9.5	5150.0	5213.5	-1.2
8	134.5	7.43	7.7	5152.2	5252.2	-1.9
9	118.2	8.46	6.4	5055.0	5118.1	-1.2
10	105.0	9.52	5.0	5010.0	4913.1	2.0
11	95.0	10.53	4.5	5005.0	5085.5	-1.6
12	86.8	11.52	4.2	5042.5	5106.0	-1.2
13	79.3	12.61	3.0	5087.5	5226.2	-2.7
14	73.7	13.57	3.2	5077.5	5219.0	-2.7
15	68.5	14.60	2.7	5082.5	5029.7	1.0
16	64.2	15.58	2.7	5077.5	5115.4	-0.7
18	56.6	17.67	1.9	5047.5	5064.2	-0.3
20	50.8	19.69	1.6	4975.0	4905.4	1.4
22	45.8	21.83	0.8	5000.0	4912.5	1.8
24	42.0	23.81	0.8	4997.5	5111.9	-2.2
26	38.4	26.04	-0.2	4970.0	5016.9	-0.9
28	35.6	28.09	-0.3	4982.5	5030.3	-1.0
30	33.3	30.03	-0.1	5250.0	5169.2	1.6
35	28.2	35.46	-1.3	5037.5	5169.6	-2.6
40	24.6	40.65	-1.6	5062.5	5303.7	-4.5
45	21.8	45.87	-1.9	3950.0	4174.3	-5.4
50	19.7	50.76	-1.5	2985.0	3261.5	-8.5

Note: $\text{Percent error} = \dfrac{\text{RR2008 value} - \text{measured value}}{\text{measured value}} \times 100$.

1 lb = 4.448 N.

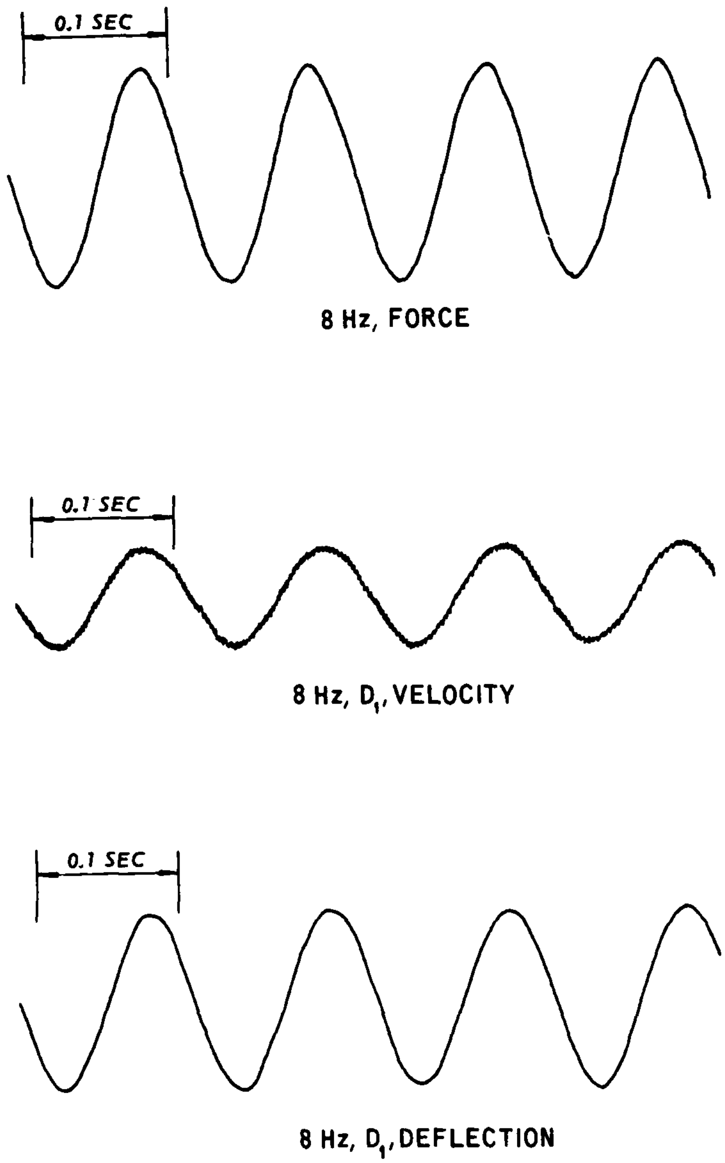

Figure 17. Dynaflect signals

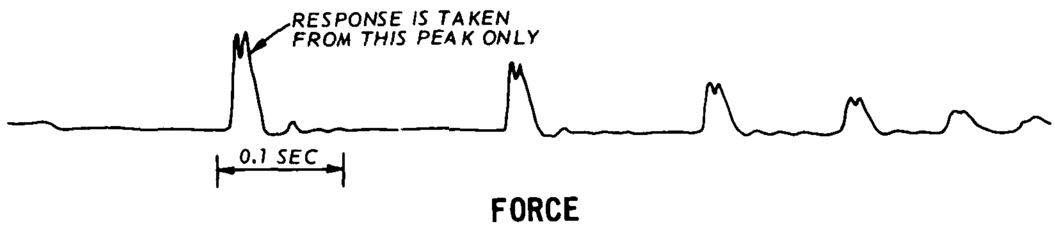

Figure 18. FWD signals

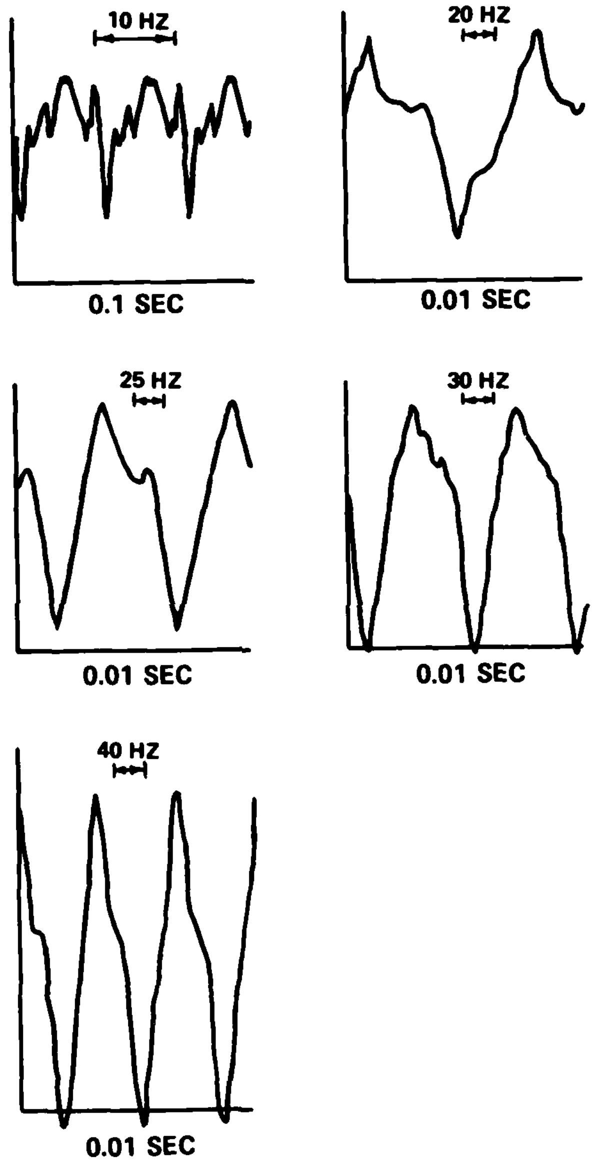

Figure 19. Model 510 Road Rater force signals

Figure 20 presents the force signals for the Model 2008 Road Rater. Note that at low frequencies the signal does not resemble a sinusoidal motion. Thus, when this signal is filtered as reported previously, there is a much better agreement to the load reported by the Model 2008. According to the manufacturer, the load signals from each of the three load cells are summed and the peaks are averaged to give the dynamic force. The signal equipment used to monitor these loads during the accuracy testing, which is the same as used by the WES 16-kip vibrator, selects the peak force signal and holds this until the voltage (signal) crosses zero. At this time, it resets and captures the next peak. Filtering of these signals provides a much improved sinusoidal motion to be sampled. Figure 21 presents the Model 2008 Road Rater velocity signals. Again, only at the higher frequencies do they even approach a sine wave. The Model 2008 deflection signals (Figure 22) are shown for three different frequencies. Even after integration the signal at 5 Hz is ragged. Both the 15- and 26-Hz signals approach a sine wave.

To compare the signals of these devices, the force, velocity, and deflection signals from the WES 16-kip vibrator are presented. The force signals (Figure 23) are ragged below 10 Hz and above 35 Hz. Between these extremes, the sinusoidal motion is good. This band is narrowed for the velocity signals between 15 Hz and 24 Hz (Figure 24). Deflection signals are shown for three frequencies (Figure 25). As with the Model 2008 Road Rater, the 5-Hz signal is very ragged, whereas the 15- and 25-Hz signals are sinusoidal.

DEPTH OF SIGNIFICANT INFLUENCE

The determination of the depth of significant or measurable dynamic influence from the various devices was accomplished by placing velocity transducers in the pavement foundation at different depths. Deflections were then measured at the different depths as a result of the input loading. The loading device was located directly over the velocity transducer and at various offset distances to evaluate the capability of the input loading to adequately excite the entire pavement

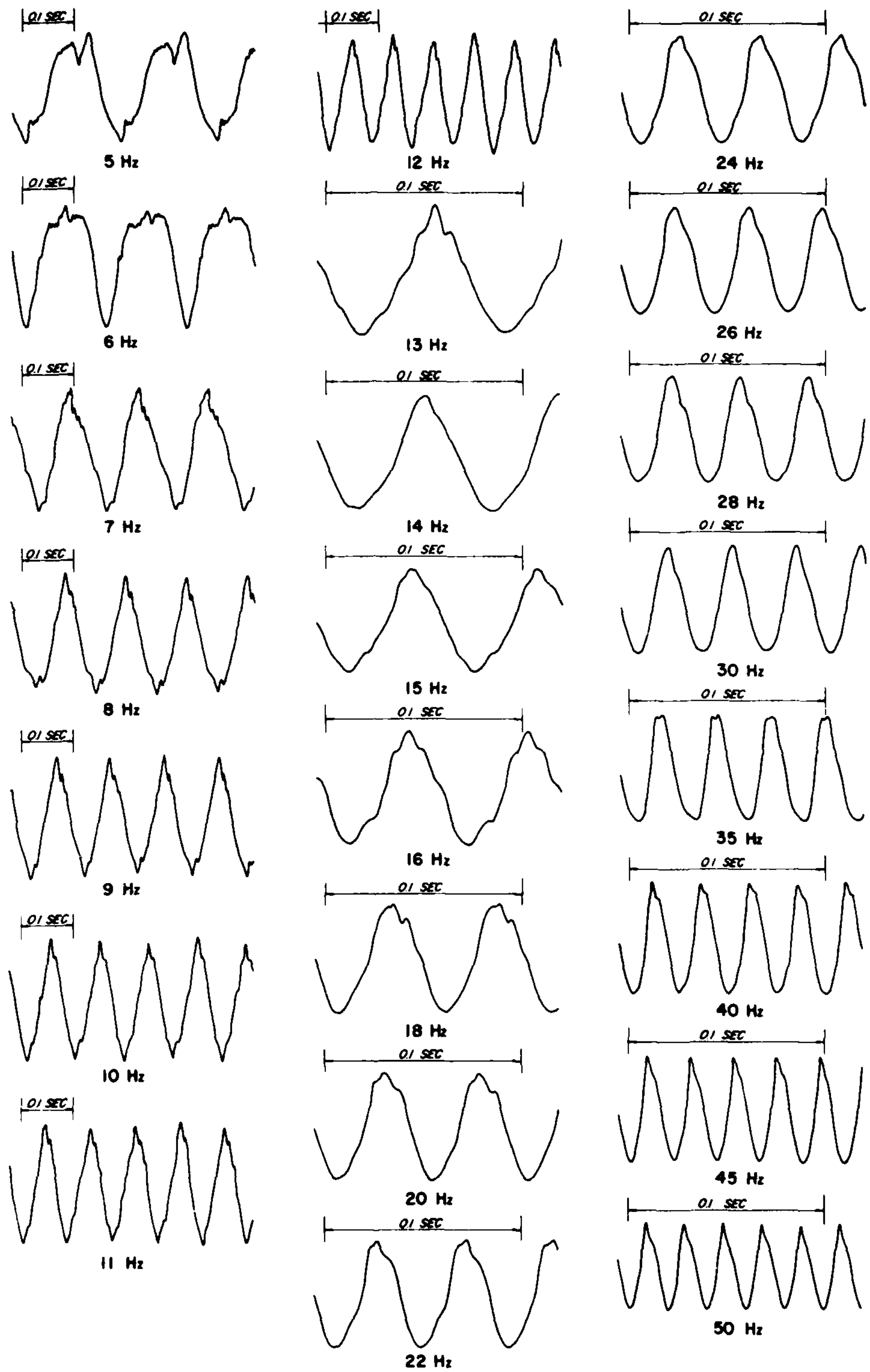

Figure 20. Model 2008 Road Rater force signals

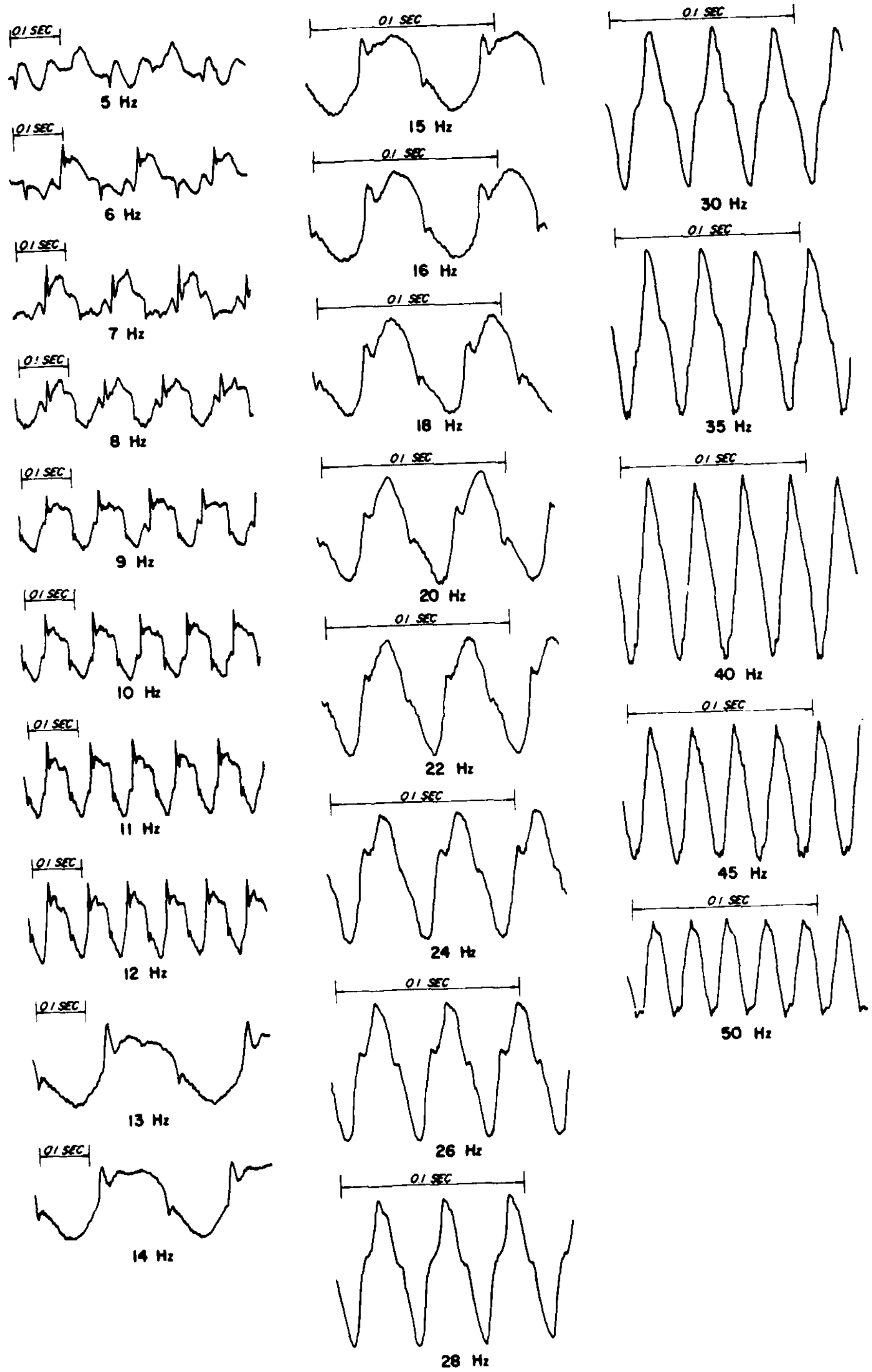

Figure 21. Model 2008 Road Rater velocity signals

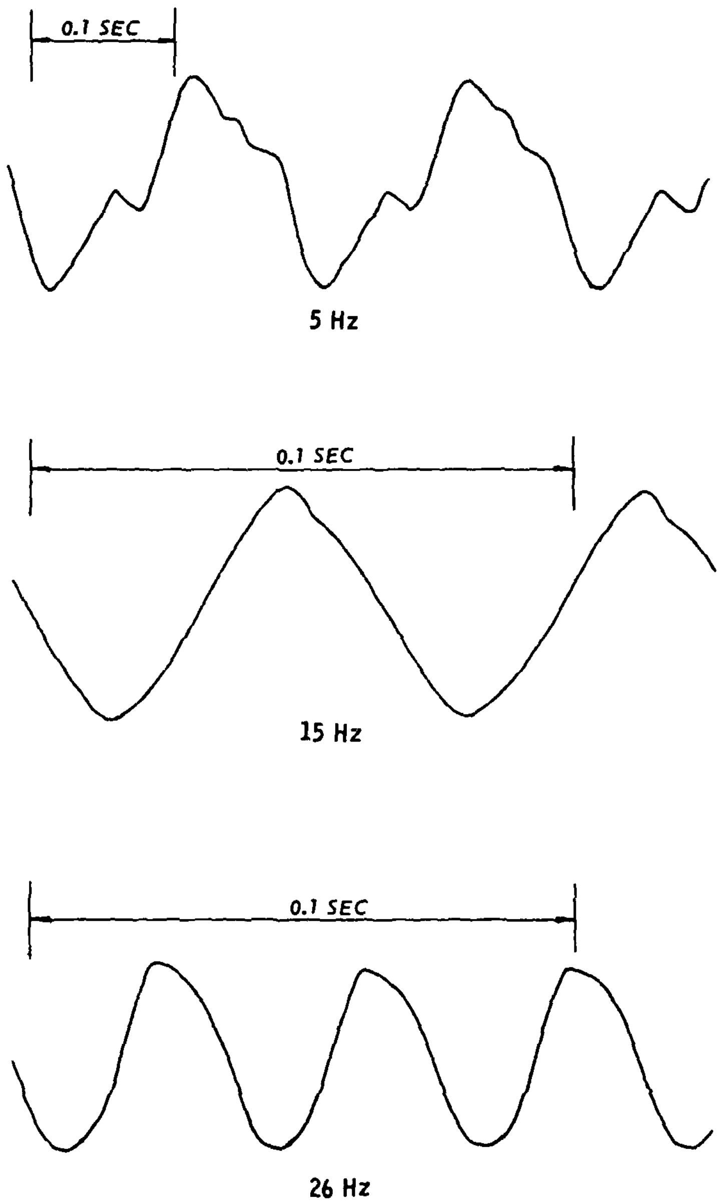

Figure 22. Model 2008 Road Rater deflection signals

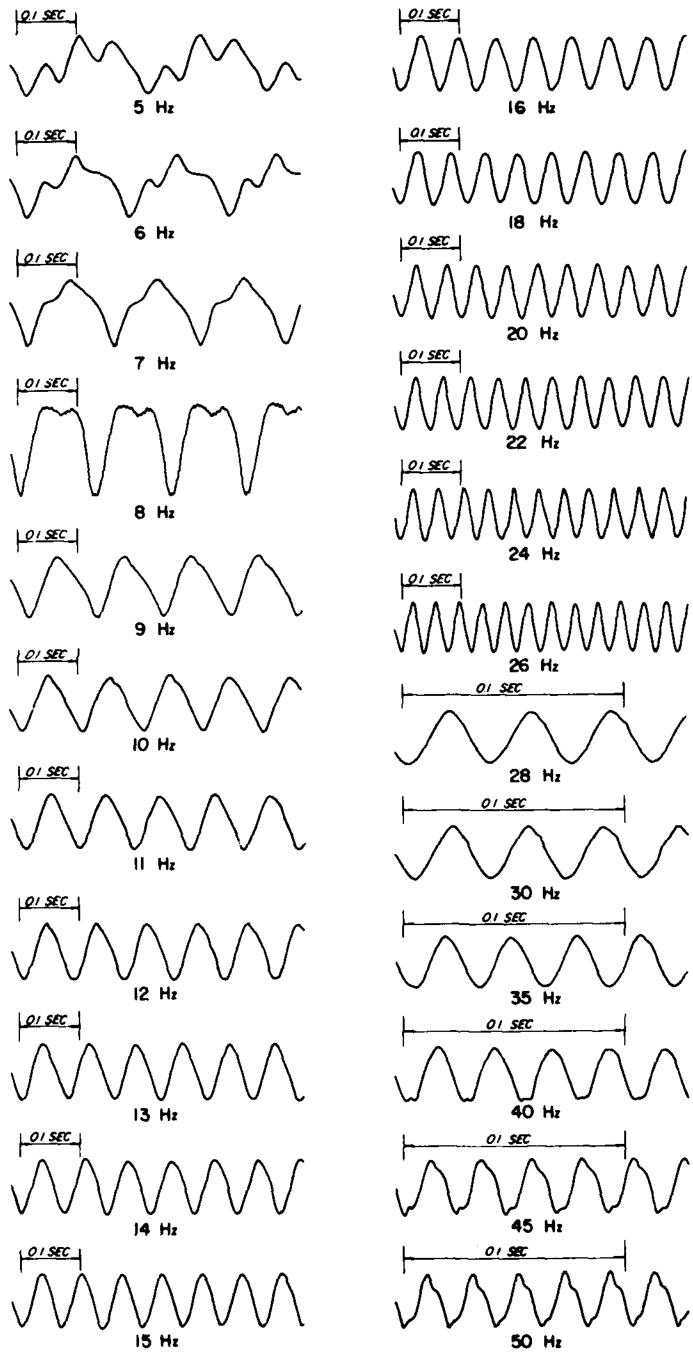

Figure 23. WES 16-kip vibrator force signals

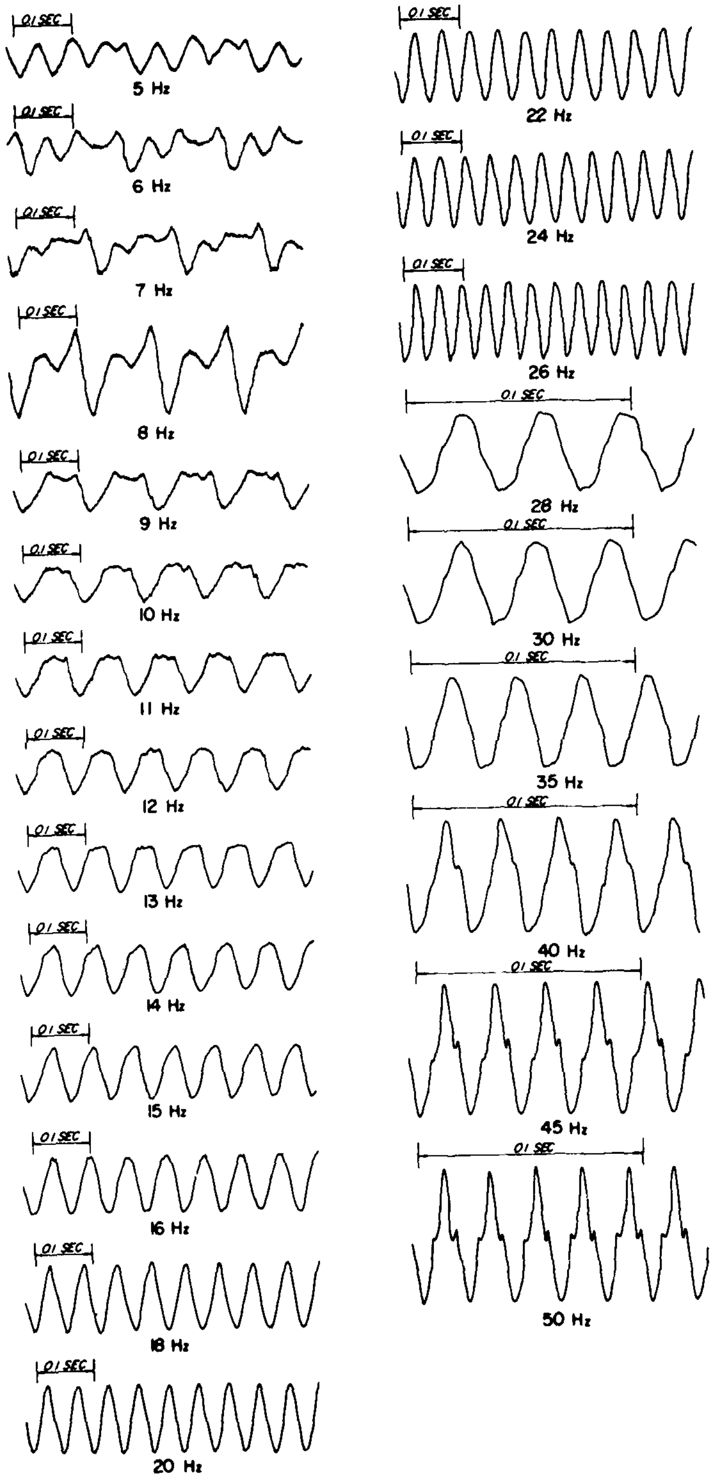

Figure 24. WES 16-kip vibrator velocity signals

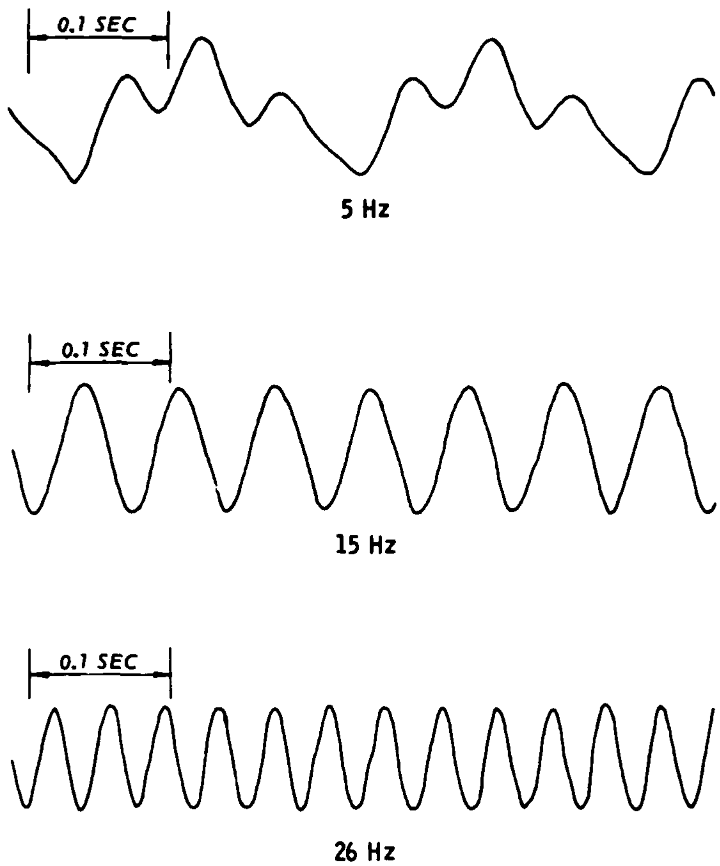

Figure 25. WES 16-kip vibrator deflection signals

structure. Two existing pavement test sections at the WES were selected for these tests. One section consisted of an asphaltic concrete (AC) overlay over portland cement concrete (PCC) pavement placed directly over a lean clay subgrade. Velocity pickups were placed in the subgrade prior to placing the PCC. Figure 26 shows a layout of this AC/PCC test section. The other section was an AC pavement with a 4-in. (10-cm) AC over 7-in. (17.8-cm) crushed stone base over a 26-in. (66-cm) sand-gravel subbase over a lean clay subgrade. Figure 27 presents a layout of this AC test section with the velocity sensors.

Results from the depth of influence tests are presented in the form of deflection contour lines plotted versus depth and distance from

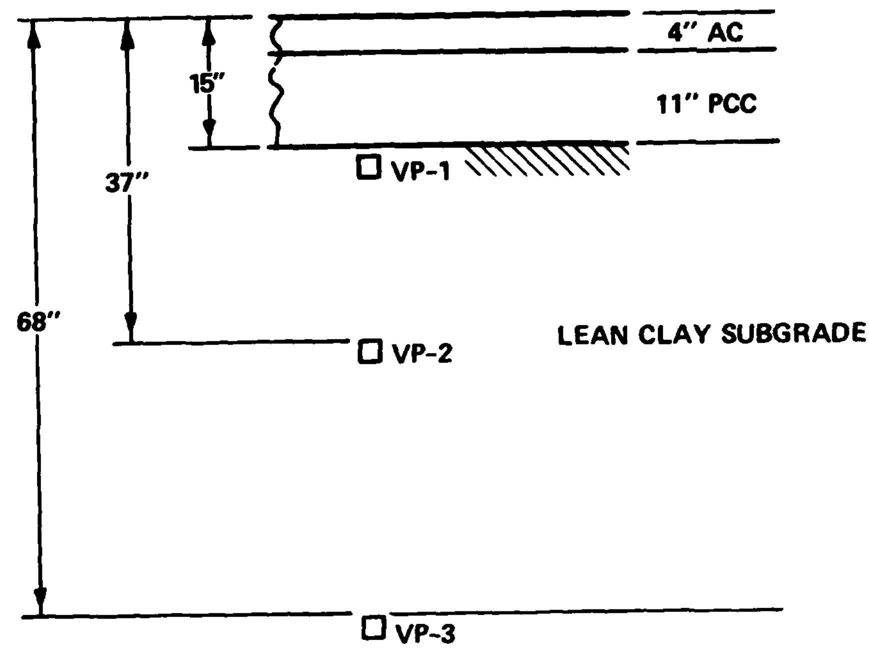

Figure 26. Layout of the AC/PCC instrumentation section (1 in. = 2.54 cm)

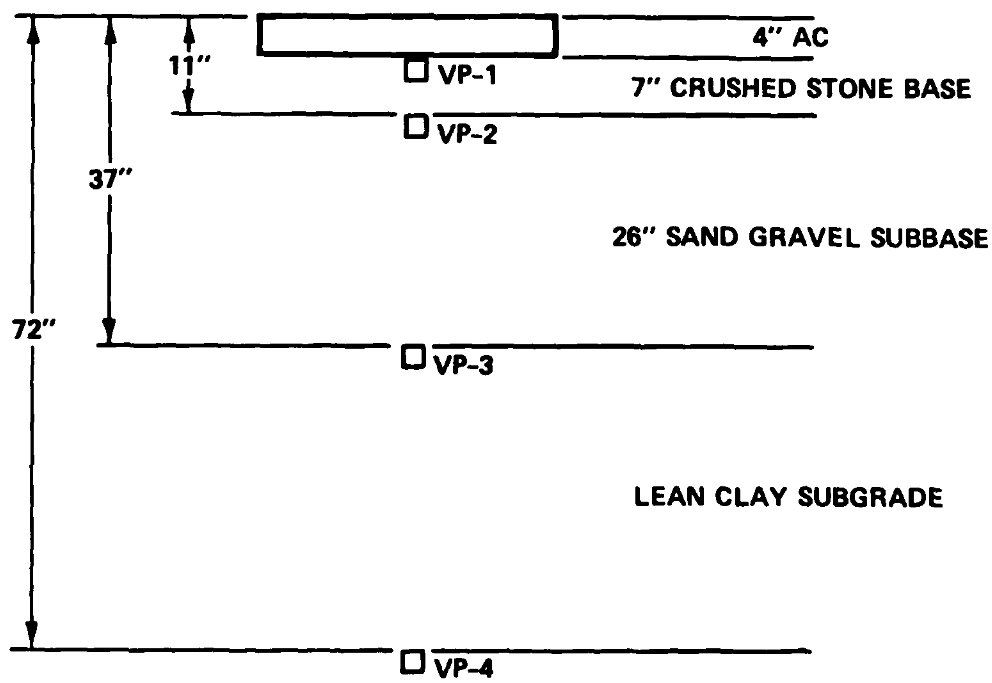

Figure 27. Layout of the AC instrumentation section (1 in. = 2.54 cm)

the applied load. Figure 28 shows the test results of the Dynaflect and the WES 16-kip (7.3-metric ton) vibrator operating at the same load and frequency on the AC section. Note that the Dynaflect has higher deflections near the surface and center of the load. This is due to the smaller contact area. Away from this area, the contours are similar. The FWD tests on the AC section (Figure 29) produced about 10 times greater deflections than the Dynaflect at the 60-in. (1.5-m) depth. Figure 30 illustrates the contours for the Model 2008 Road Rater and the WES 16-kip vibrator operating at 15 Hz and 7,000-lb (31,138-N) force. These deflections at 60 in. (1.5 m) are similar to those for the FWD but are less near the surface under the applied load. Again, the contact pressure is greater for the FWD. (One hundred psi (70,310 kg/m^2) for the FWD and 27.5 psi (19,335 kg/m^2) for the Model 2008 Road Rater.) Tests were not conducted on these sections with either the Model 400 or Model 510 Road Rater.

Figure 31 shows the depth of influence contours for the Dynaflect and the WES 16-kip vibrator on the AC/PCC instrumented section. The deflections of the WES 16-kip vibrator are greater than those for the Dynaflect at all locations but particularly near the surface. This could be attributed to the mass of the vibrator. The higher contact pressure for the Dynaflect will have little significance on the PCC pavement due to the stiffness of the upper layer. The FWD tests on the AC/PCC section (Figure 32) again obtained roughly 10 times the deflection of the Dynaflect with depth. Figure 33 illustrates the results of the Model 2008 Road Rater and WES 16-kip vibrator tests. As expected, these deflection contours are less than the FWD. To compare all deflections, the WES 16-kip vibrator was tested at a normal operating force level of 10,000 lb (44.48 kN) peak (20,000 lb (88.96 kN) peak to peak). The tests results shown in Figure 34 indicate that these deflections are 3 to 4 times the values of the FWD and Model 2008 Road Rater, and 25 times the Dynaflect.

SUITABILITY FOR USE IN EVALUATING LIGHT AIRCRAFT PAVEMENTS

Suitability for use in evaluating light aircraft pavements was

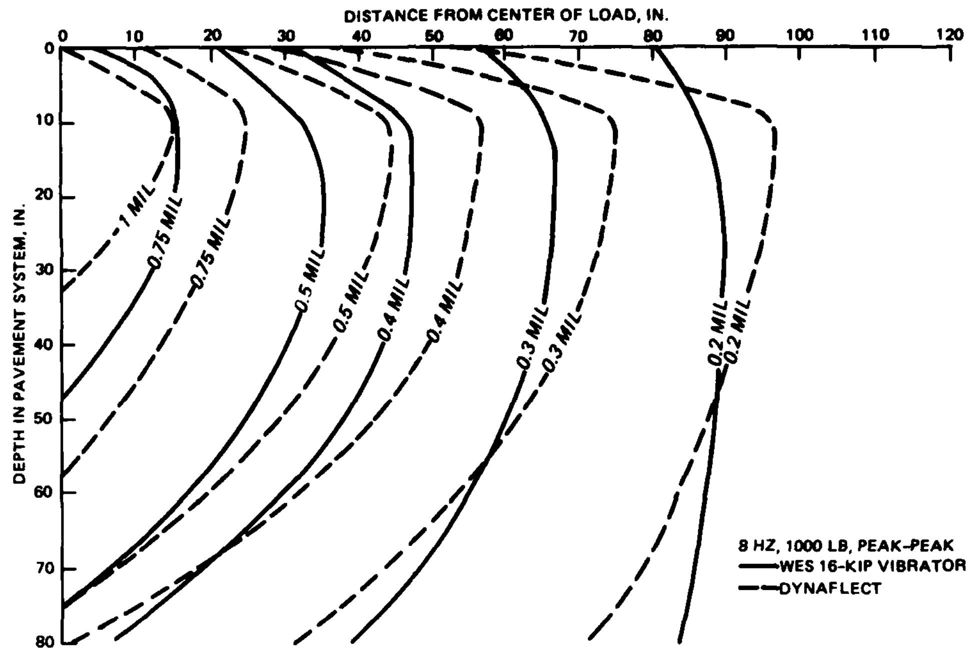

Figure 28. Depth of influence contours for the Dynaflect and the WES 16-kip vibrator on the AC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

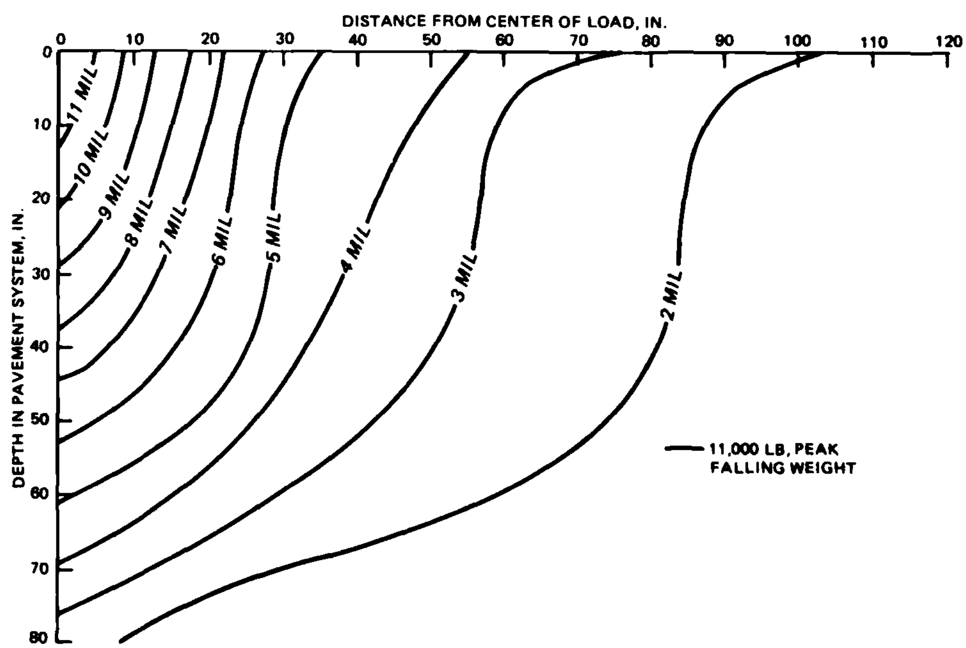

Figure 29. Depth of influence contours for the FWD on the AC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

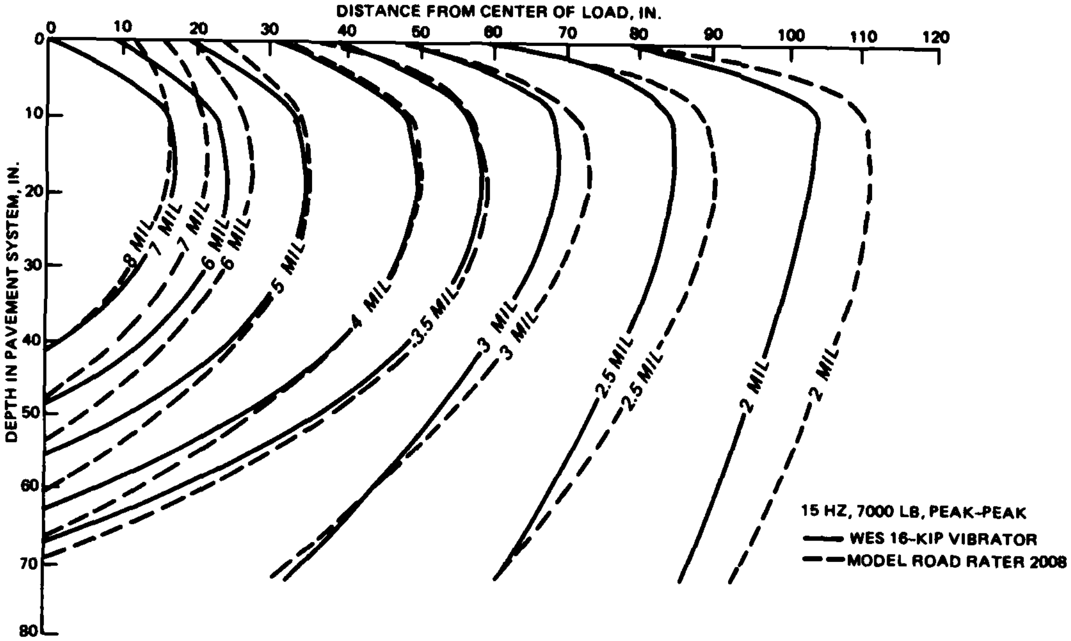

Figure 30. Depth of influence contours for the Model 2008 Road Rater and the WES 16-kip vibrator on the AC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

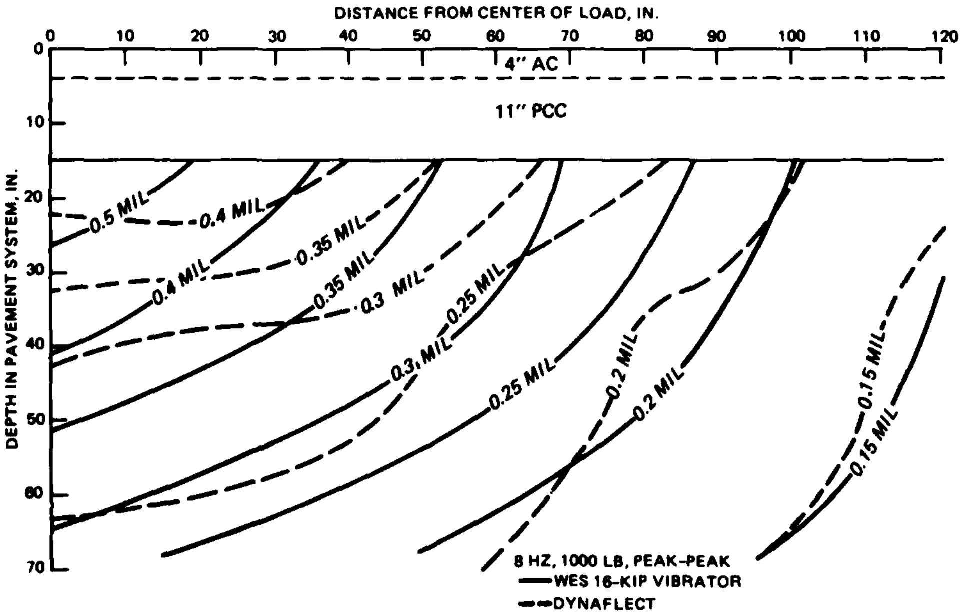

Figure 31. Depth of influence contours for the Dynaflect and the WES 16-kip vibrator on the AC/PCC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

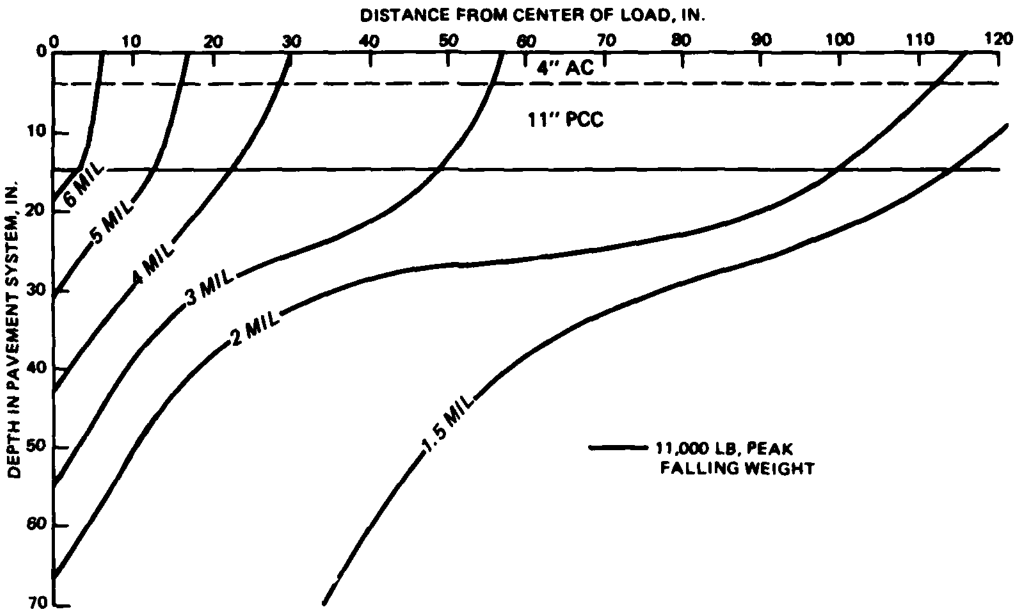

Figure 32. Depth of influence contours for the FWD on the AC/PCC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

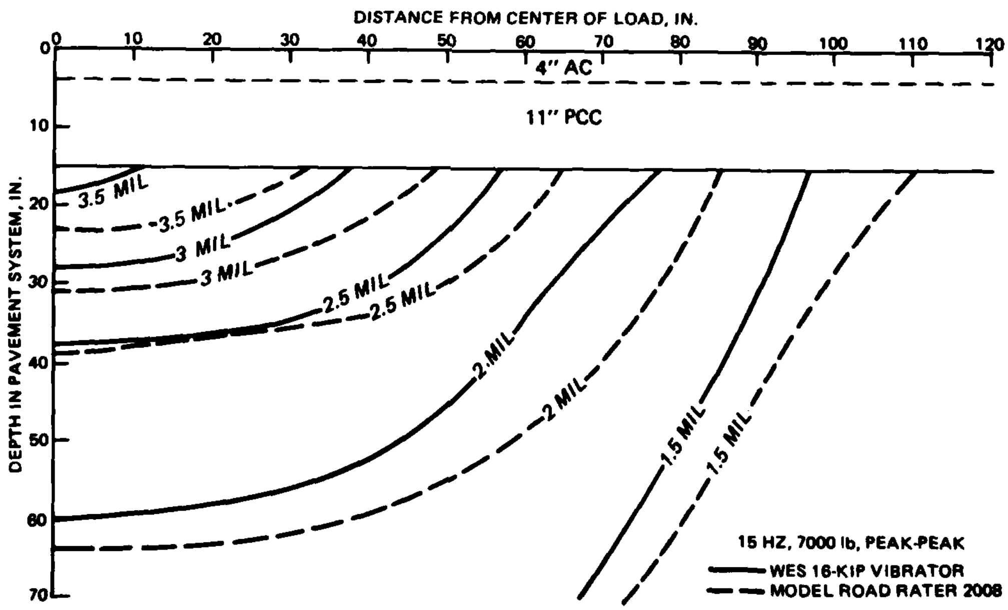

Figure 33. Depth of influence contours for the Model 2008 Road Rater on the AC/PCC instrumented section (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

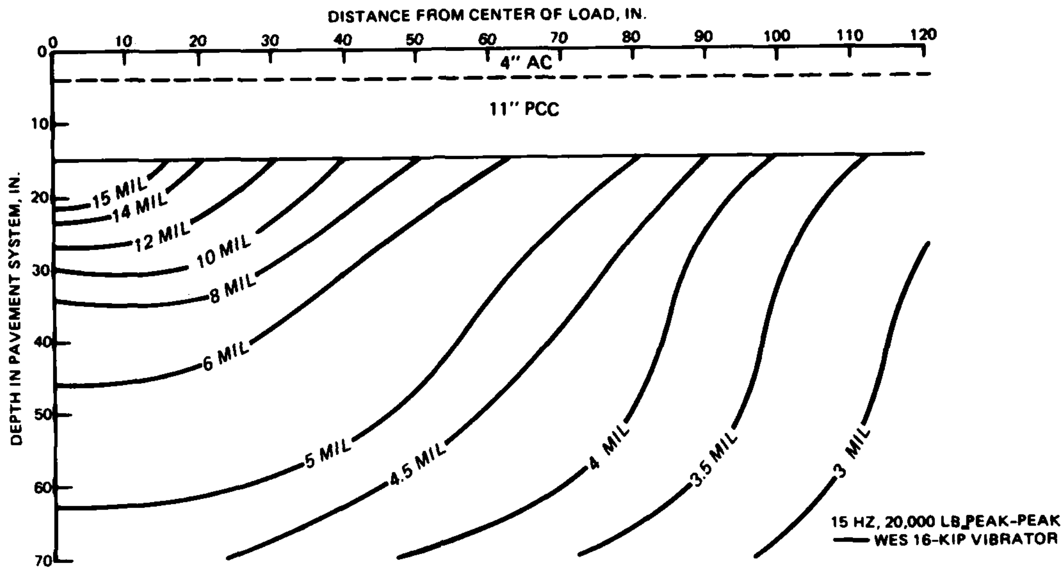

Figure 34. Depth of influence contours for the WES 16-kip vibrator on the AC/PCC instrumented section operating at a normal force level (1 mil = 25.4 microns; 1 in. = 2.54 cm; 1 lb = 4.448 N)

rated in the final analysis based upon the ability of the input loading to produce a pavement response of sufficient magnitude to achieve consistently reliable measurements for a full range of light aircraft pavement thicknesses and foundation conditions.

PENNSYLVANIA TRANSPORTATION RESEARCH FACILITY TESTS

The Pennsylvania Transportation Research Facility (PTRF), described by Kilareski et al.,* was used as one of the field test sites. The PTRF has 21 flexible pavement test sections with varying thicknesses of AC, base and subbase (Figure 35). Three of the sections, 9, H, and 14, were rutted and thus were not tested. Sections 1a-1d, 7, and 8 were superelevated. The Models 400, 510, and 2008 Road Raters, the Dynaflect,

* W. P. Kilareski et al., "Modification Construction and Instrumentation of an Experimental Highway," Report No. PTI7607, Pennsylvania Department of Transportation, Harrisburg, Pa., 1976.

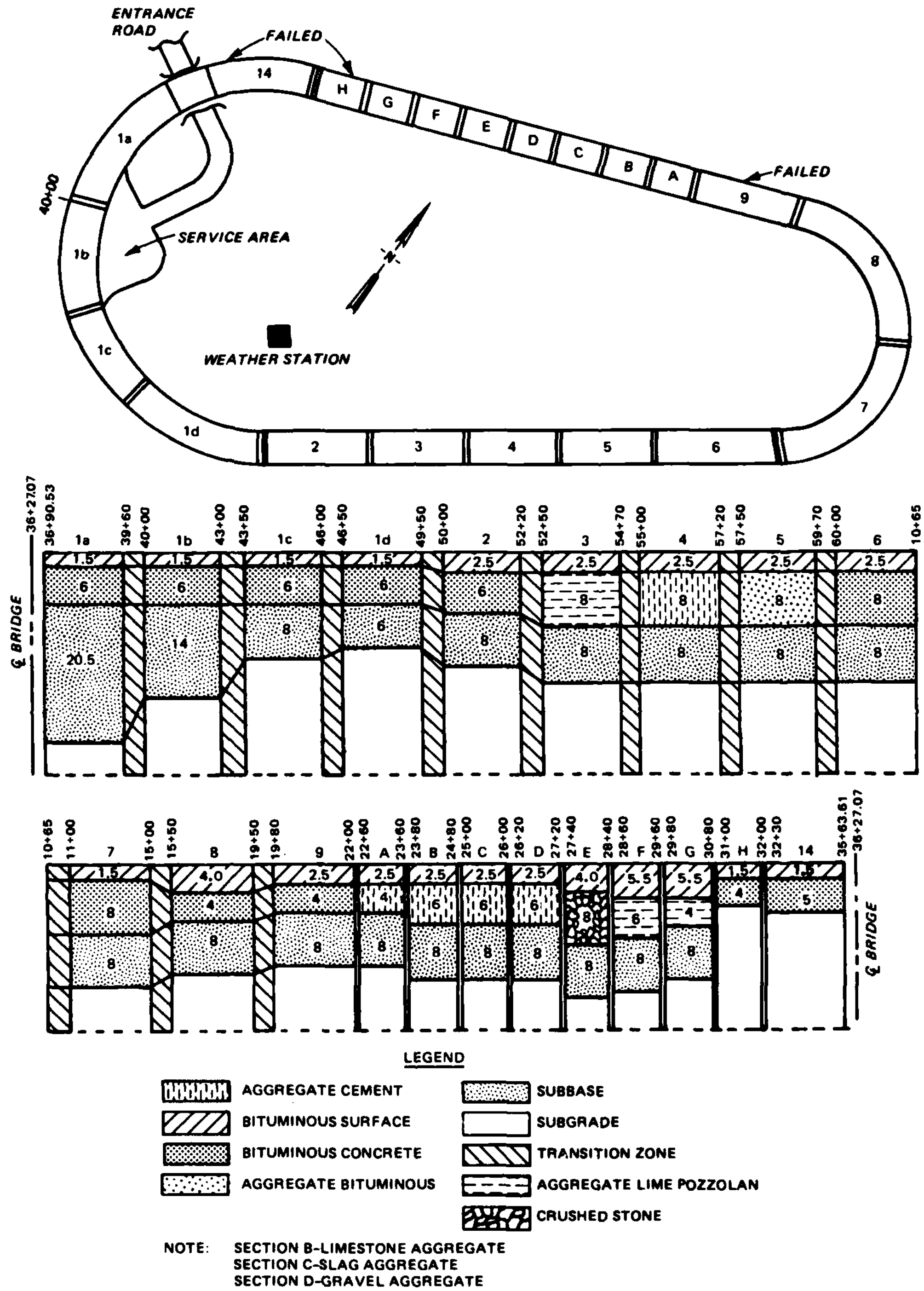

Figure 35. Layout and description of pavements at the PTRF (thicknesses are in inches; 1 in. = 2.54 cm)

and the WES 16-kip vibrator were used in the testing. Tests were conducted at 25-ft (7.6-m) intervals alternating between the inner and outer wheel paths. In addition, four Benkelman Beam tests were conducted in each section at designated positions. These were paired tests with one in each wheel path. The beam testing was completed two weeks prior to the dynamic testing. Additional tests with the vibrators were conducted in the shorter alphabetically labeled sections to give a better statistical average. Generally, there were 8 to 15 test locations in each test section. These additional tests were located in the opposite wheel paths. Table 14 presents the loads and frequencies at which the vibrators were tested.

Table 14

Test Loads and Frequencies for Vibrators

Device	Frequency Hz	Dynamic Load Peak to Peak lb
Dynaflect	8	1000
Model 400 Road Rater	25	726
Model 510 Road Rater	25	1800
Model 2008 Road Rater and WES 16-kip vibrator	8	1000
	25	1800
	15	1000
	15	3000
	15	5000
	15	7000

Note: In addition to the above tests, a load sweep was conducted with the WES 16-kip vibrator at 15 Hz with the load varied from 0 to 15,000 lb (1 lb = 4.448 N).

Temperature adjustment. During the testing at PTRF, the surface temperature of the pavement was monitored at regular intervals. Using the Asphalt Institute method,* which incorporates the previous five-day mean air temperature, asphalt thickness, and surface temperature, mean pavement temperatures were calculated for all test items and test

* Asphalt Institute, op. cit., p. 3.

times. Mean pavement temperatures varied from a low of 68°F to a high of 98°F. To establish an adjustment for temperature, selected test points in items of varying AC thickness were tested with each device at periods of high and low temperatures. Results from these tests were inconclusive since the extreme high and low temperature times could not be anticipated. There was a trend in these data which indicated that the adjustments given by Green and Hall* would apply. Further study indicated that the corrections for the Benkelman Beam by the Asphalt Institute bisect the geometric center of the Green and Hall* correction (Figure 36). Additional temperature adjustment data were obtained from the Minnesota Department of Transportation. These data were taken with a Model 2000 Road Rater on conventional and full-depth asphalt pavements. The results also presented in Figure 36 show that the conventional pavement correction is near the 4-in. (10.2-cm) asphalt curve and that full-depth approaches the 8-in. (20.3-cm) curve. Based on these factors, it was decided to use the WES correction factors for the PTRF temperature correction. For the DSM, the adjustment factors are multiplied times the measured DSM to obtain the corrected value. For deflection, the adjustment factors are divided into the measured deflection to give the corrected deflection. Sections with AC thicknesses of less than 3.0 in. (7.6 cm) were not corrected.

Test results. Average deflections for each device given in Figure 37 are corrected for temperature as described previously. For the WES 16-kip vibrator and the Model 2008 Road Rater, the frequency was 15 Hz and the force was 7000 lb (31.135 kN) peak to peak. Note that there are no data for the Model 2008 on sections 1c, 1d, and 7. This was due to the superelevation of the test track. It was discovered that the loading plate (Figure 38) would not contact the pavement evenly due to the lowering mechanisms. Also, tests were not conducted in section D because rutting would not allow the plate to rest evenly on the pavement. Figure 39 shows the coefficient of variation for each test section and each device. These coefficients correspond to the deflections

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* Green and Hall, op. cit., p. 1.

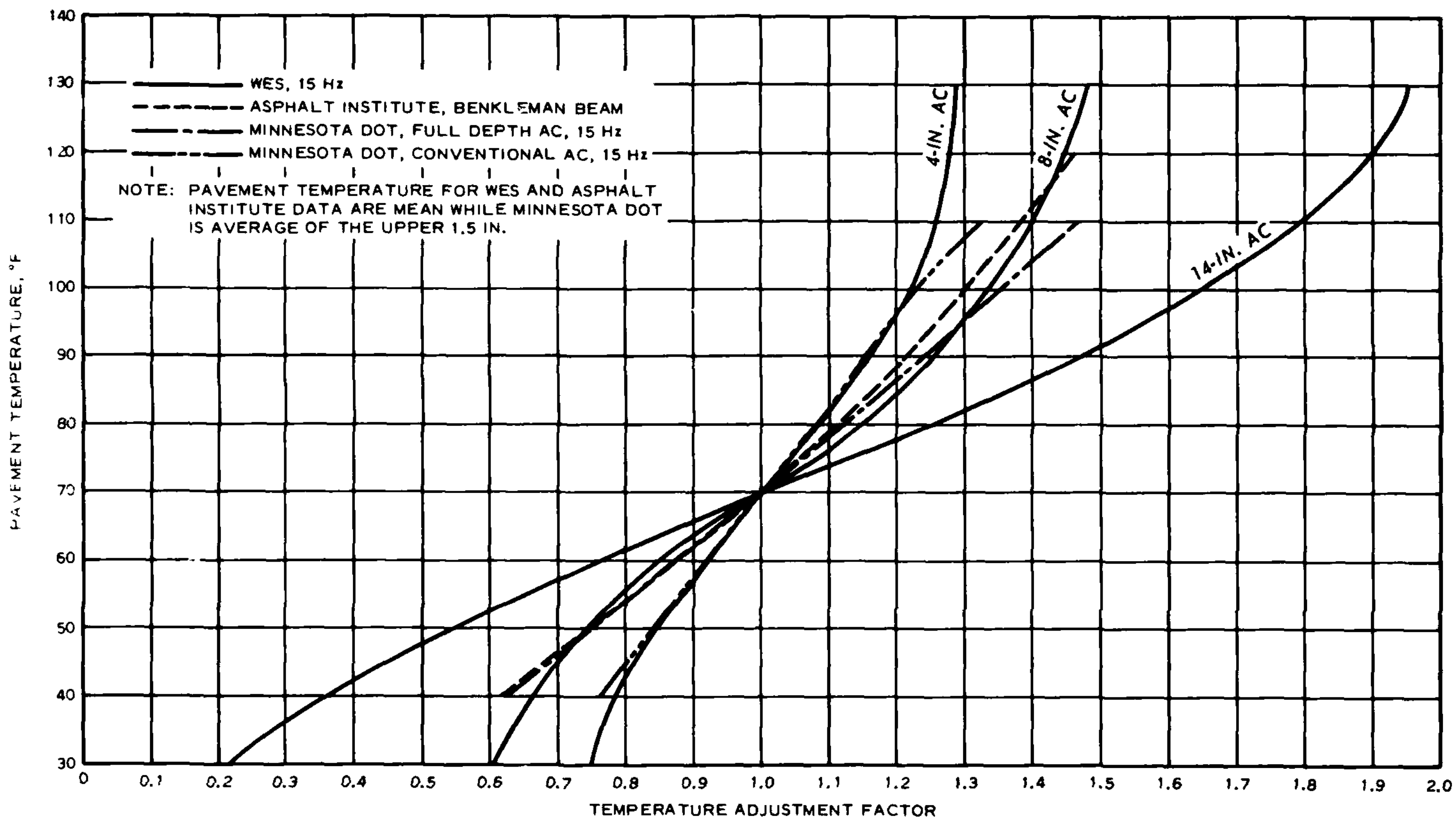

Figure 36. Comparison of temperature adjustment factors
(1 in. = 2.54 cm)

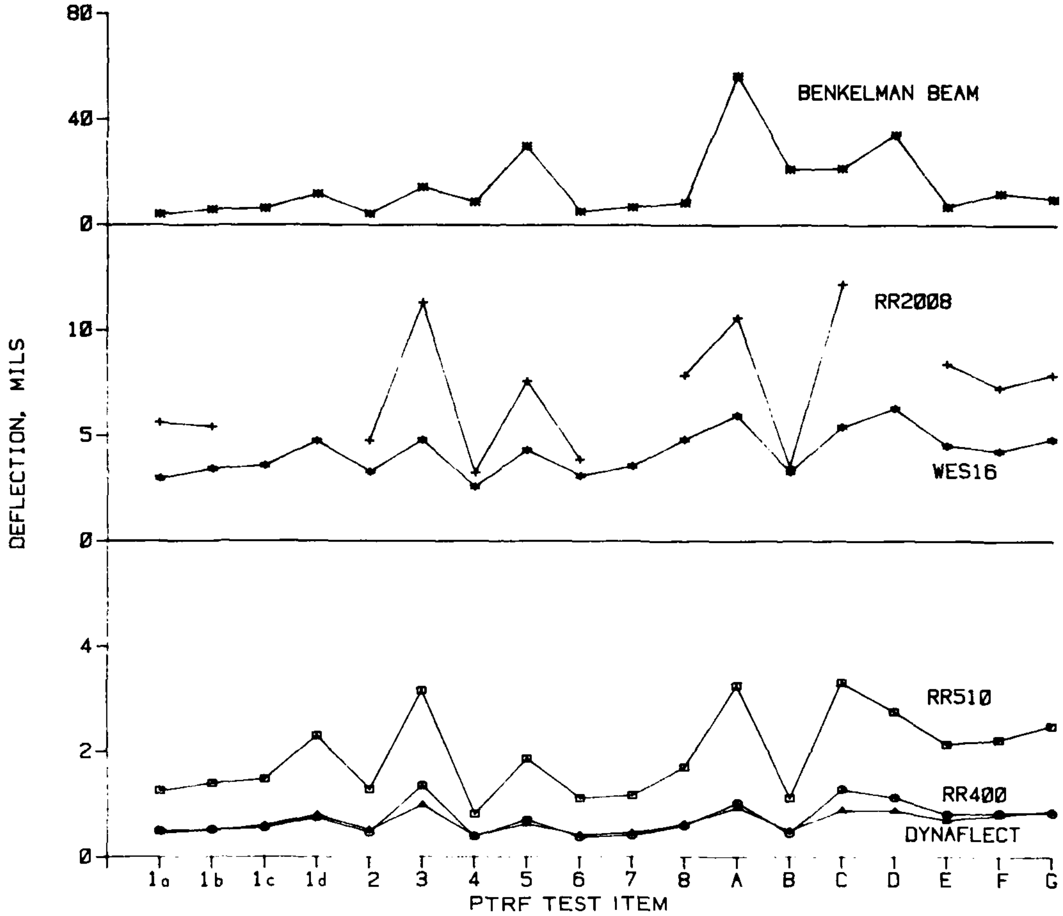

Figure 37. Average deflection in each test item for each NDT device (1 mil = 25.4 microns)

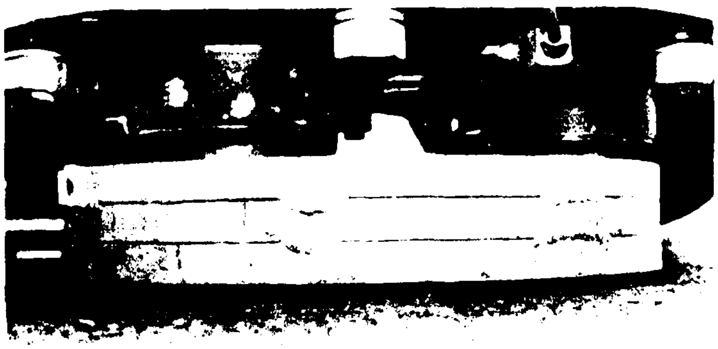

Figure 38. Model 2008 Road Rater loading plate on superelevated pavement

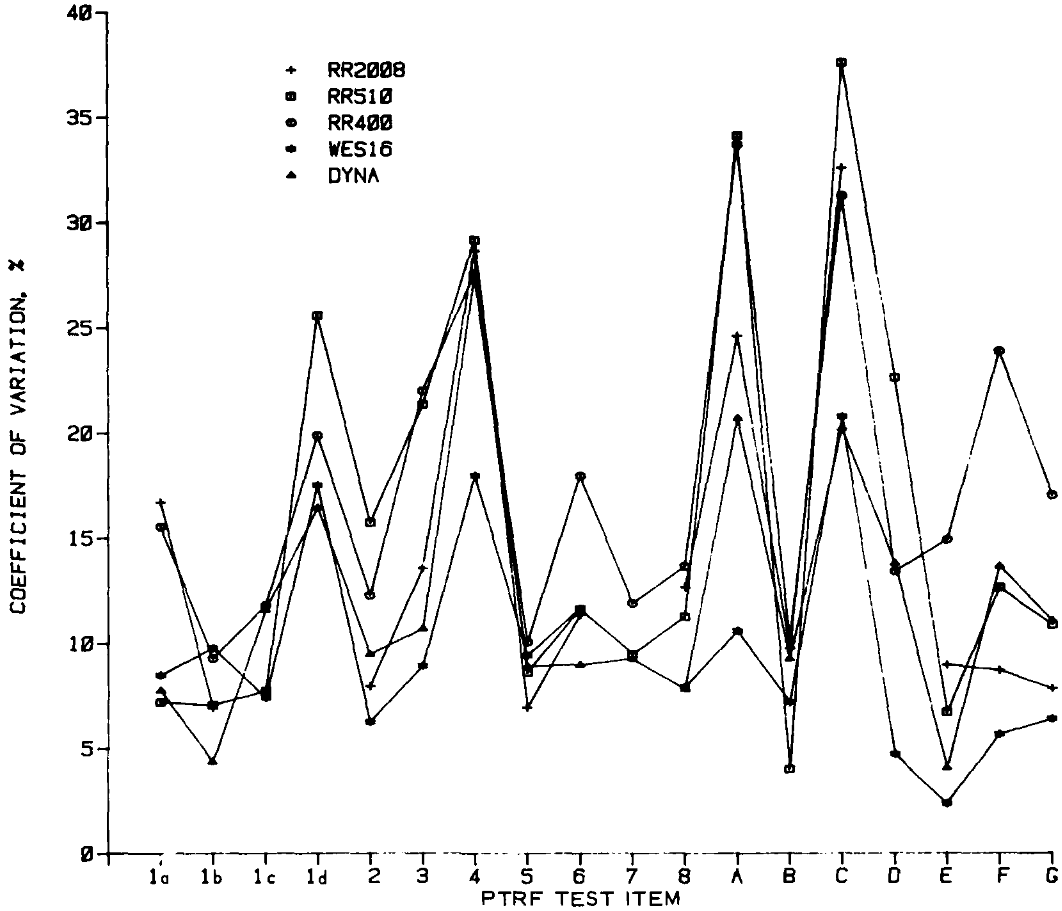

Figure 39. Coefficient of variation of measurements for each device in each test section

in Figure 37. Since only four tests were conducted with the Benkelman Beam, the coefficient of variation would be meaningless and is not presented.

The primary test for evaluating airport pavements with the WES 16-kip vibrator has been the DSM. During this test, the load is varied from 0 to 30,000 lb (133.4 kN) (peak to peak) and plotted against the resulting deflection. The DSM is defined as the slope (load/deflection) of the upper one-third portion of this line. The method for calculating the DSM is as follows:

$$\text{DSM} = \frac{28 - 20}{\Delta_{o(28)} - \Delta_{o(20)}} \text{ kips/in.}$$

where

DSM = Dynamic Stiffness Modulus, kips/in.

28 - 20 = selected peak-to-peak force levels, kips

$\Delta_{o(28)}$ = deflection of the loading plate from the 28-kip (124.5 kN) load, in., peak to peak

$\Delta_{o(20)}$ = deflection on the loading plate from the 20-kip (88.96 kN) load, in., peak to peak

Since the Model 2008 Road Rater has the capability to vary loads as the WES 16-kip vibrator, another stiffness was calculated for comparison during this study. Since the mass of the Model 2008 Road Rater is one-fourth the size of the WES 16-kip, the force values in the DSM equation were divided by four and the DSM is termed LDSM. A DSM value for the WES 16-kip vibrator was computed at force levels comparable to the Model 2008 and is also termed LDSM. Therefore, the resulting modulus is expressed as

$$LDSM = \frac{F_{(7)} - F_{(5)}}{\Delta_{o(7)} - \Delta_{o(5)}} \text{ kips/in.}$$

where

$F_{(7)}$, $F_{(5)}$ = force level within 10 percent of 7 or 5 kips (31.1 or 22.2 kN) peak to peak

$\Delta_{o(7)}$ = deflection associated with the 7-kip (31.1-kN) force, in., peak to peak

$\Delta_{o(5)}$ = deflection associated with the 5-kip (22.2-kN) force, in., peak to peak

All modulus testing was conducted at 15-Hz frequency. In some cases for the DSM, the resulting deflection associated with the 20- and 28-kip (88.96- and 124.5-kN) loads would be of a magnitude that exceeded the range of the velocity sensors. Therefore, the force would be terminated at that point. The DSM in a case such as this would be the slope of the upper one-third portion of the plotted line. The lower plot of Figure 40 shows a comparison of the average values for each test item of the PTRF. A very interesting note is that the Model 2008 Road Rater LDSM tracks very close to the DSM, not the LDSM. Also shown in Figure 40 is the coefficient of variation for each test item. The high

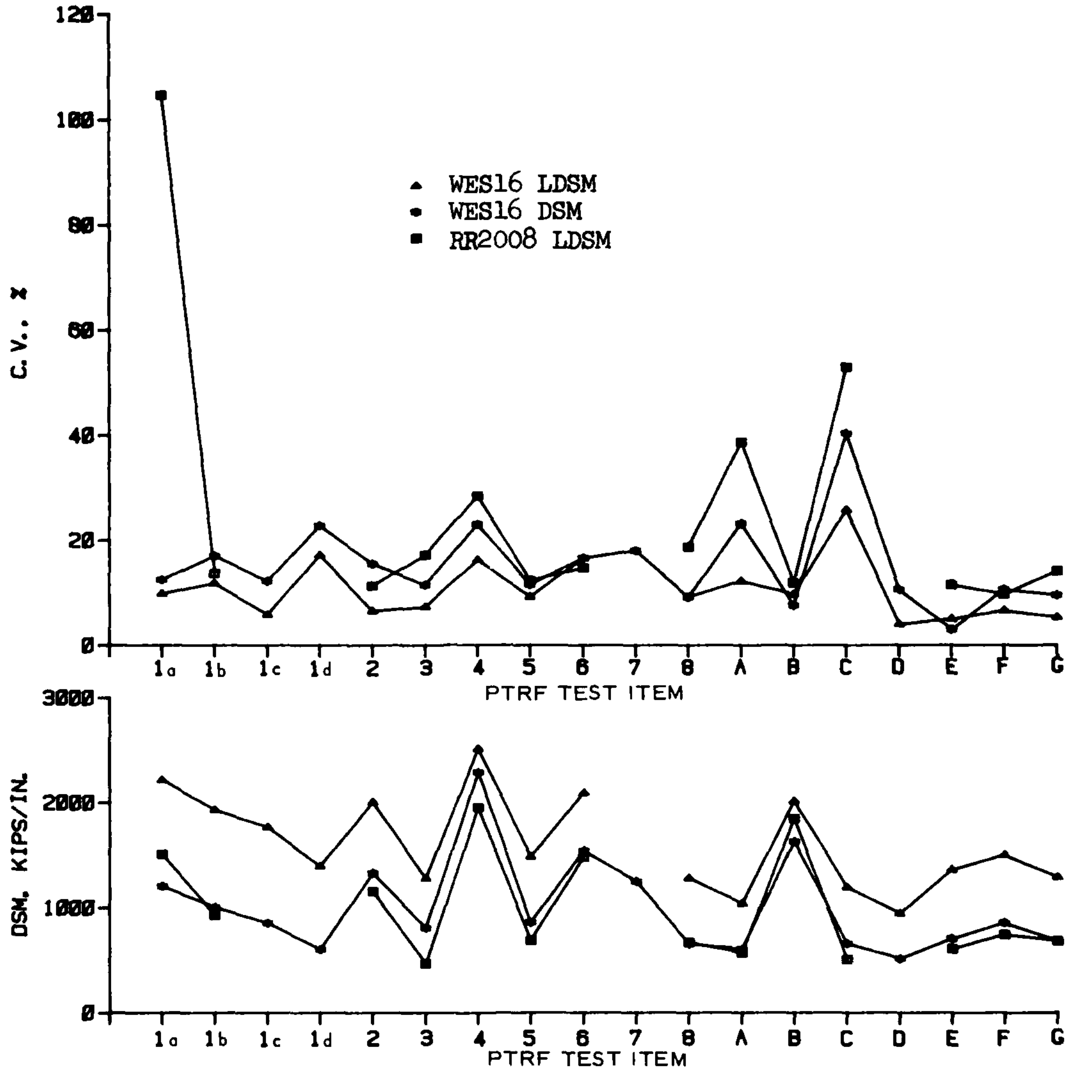

Figure 40. Comparison of DSM averages and coefficient of variation for the Model 2008 Road Rater and the WES 16-kip vibrator (kips/in. = 1.75 kN/cm)

variability of the Model 2008 Road Rater in items 1a, a, and c could be attributed to the superelevation in 1a, and slight rutting in sections A and C.

PTRF data comparisons. To statistically compare the data taken at the PTRF, two computer programs were used. The first calculated the

best fit line through the origin. The second program fit six different curves to the data. These possible curves are given as

$$y = a + Bx$$
$$y = Ae^{Bx}$$
$$y = Ax^{B}$$
$$y = A + B/x$$
$$y = 1/(A + Bx)$$
$$y = x/(A + Bx)$$

To compare these data, only those test locations where both of the devices in question were tested were used. The results of the comparisons with the Benkelman Beam (Table 15) show that very poor correlations were obtained in all cases. The comparisons for the Dynaflect (Table 16) indicate that good correlation was obtained when compared with the WES 16-kip DSM. The Model 400 Road Rater comparisons (Table 17) show that a fair correlation is obtained with the WES 16-kip DSM. The comparisons for the Model 510 Road Rater (Table 18) show that the best correlation with DSM is obtained in this case. Table 19 presents the comparisons for the Model 2008 Road Rater. Summaries of these tables are given in the analysis portion of this report.

TESTING ON PCC PAVEMENT

Tests were conducted on a PCC road at the WES with the WES 16-kip vibrator, the Dynaflect, and the Model 2008 Road Rater. The Benkelman Beam and the FWD were also used in a limited number of test locations. The pavement section on this road consisted of a 6-in. (15.2-cm) wire-reinforced PCC over a 6-in. (15.2-cm) clay gravel base over a lean clay subgrade. Figure 41 presents the results of deflection tests, which show a close relationship between deflections of the Model 2008 Road Rater and the WES 16-kip vibrator and no relationship with deflection of the Benkelman Beam. Figure 42 compares the slope of the deflection basin measurements from the Dynaflect, the Model 2008 Road Rater, and the WES 16-kip vibrator. The deflection basin is defined as a ratio of the deflection 36 in. (91.4 cm) from the center of the applied load divided by the deflection at the applied load. The Dynaflect follows

Table 15

PTRF Regression Analysis for the Benkelman Beam

Y			X			Comparison Parameters		Temperature Corrected	Line Through "O" Y = AX		Curve			
Device	Freq	Force	Device	Freq	Force				A	Correlation Coefficient	Equation	A	B	Correlation Coefficient
WES16	15 Hz	VAR**	BENK	--	--	DSM	Δ_o	Yes	0.25670+05*	-0.29061	$Y = \frac{X}{(A + BX)}$	-167608.7	391.2929	0.23647
WES16	15 Hz	VAR	BENK	--	--	DSM	Δ_o	No	0.22243+05	-0.36689	$Y = \frac{1}{(A + BX)}$	0.000936	0.011026	0.41059
RR510	25 Hz	1800	BENK	--	--	Δ_o	Δ_o	Yes	0.68781-01	0.43900	$Y = \frac{X}{(A + BX)}$	0.159374	98.25233	0.12378
RR510	25 Hz	1800	BENK	--	--	Δ_o	Δ_o	No	0.59657-01	0.37282	$Y = Ae^{BX}$	0.001544	8.608665	0.39418
RR400	25 Hz	726	BENK	--	--	Δ_o	Δ_o	Yes	0.25021-01	0.43341	$Y = \frac{X}{(A + BX)}$	0.098273	16.64430	0.22134
RR400	25 Hz	726	BENK	--	--	Δ_o	Δ_o	No	0.21636-01	0.27189	$Y = \frac{1}{(A + BX)}$	1775.236	-9865.996	0.31166
RR2008	15 Hz	1000	BENK	--	--	Δ_o	Δ_o	Yes	0.20998+00	0.31949	$Y = \frac{1}{(A + BX)}$	345.6115	-20061.74	0.15180
RR2008	15 Hz	1000	BENK	--	--	Δ_o	Δ_o	No	0.19986+00	0.25779	$Y = Ae^{BX}$	0.005785	5.667166	0.27212
WES16	15 Hz	7000	BENK	--	--	Δ_o	Δ_o	Yes	0.13712+00	0.52352	$Y = \frac{X}{(A + BX)}$	1.395933	-164.1464	0.25929
WES16	15 Hz	7000	BENK	--	--	Δ_o	Δ_o	No	0.12122+00	0.44296	$Y = A + (BX)$	0.003719	0.025868	0.44296
RR2008	15 Hz	VAR	BENK	--	--	LDSM	Δ_o	Yes	0.23398+05	-0.17535	$Y = \frac{X}{(A + BX)}$	-82529.73	317.4510	0.12543
RR2008	15 Hz	VAR	BENK	--	--	LDSM	Δ_o	No	0.21845+05	-0.22366	$Y = \frac{1}{(A + BX)}$	0.001155	0.007027	0.23759
WES16	15 Hz	VAR	BENK	--	--	LDSM	Δ_o	Yes	0.40162+05	-0.45507	$Y = \frac{1}{(A + BX)}$	-.97.3771	0.234170	0.30148
WES16	15 Hz	VAR	BENK	--	--	LDSM	Δ_o	No	0.36360+05	-0.40290	$Y = \frac{1}{(A + BX)}$	0.000589	0.004327	0.41640

* Indicates 0.2567×10^5.
** Variable.

Table [illegible]

PTRF Regression Analysis for the Dynaflect

Y Device	Y Freq	Y Force	X Device	X Freq	X Force	Comparison Parameters		Temperature Corrected	Line Through "O" Y = AX: A	Line Through "O" Y = AX: Correlation Coefficient	Curve: Equation	Curve: A	Curve: B	Curve: Correlation Coefficient
WES16	15 Hz	VAR**	DYNA	6 Hz	1,000	DSM	Δ_o	Yes	0.12942+07*	-0.70652	$Y = A + (\frac{B}{X})$	-324.1692	0.795217	0.83299
WES16	15 Hz	VAR	DYNA	6 Hz	1,000	DSM	Δ_o	No	0.11420+07	[illegible]	$Y = A + (\frac{B}{X})$	-421.4592	0.884492	0.86042
WES16	6 Hz	1,000	DYNA	6 Hz	1,000	Δ_o	Δ_o	Yes	0.106[illegible]	[illegible]	$Y = \frac{X}{(A + BX)}$	0.924636	55.71729	0.76162
WES16	6 Hz	1,000	DYNA	6 Hz	1,000	Δ_o	Δ_o	No	0.10867+01	0.54593	$Y = \frac{X}{(A + BX)}$	0.980362	-7.372035	0.76466
WES16	6 Hz	1,000	DYNA	6 Hz	1,000	Δ_{36}	Δ_{36}	Yes	0.10820+01	0.17968	$Y = \frac{X}{(A + BX)}$	0.883901	876.6826	0.2 832
WES16	6 Hz	1,000	DYNA	6 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.92701+00	0.84901	$Y = A + (BX)$	0.095664	1.549286	0.59802
WES16	6 Hz	1,000	DYNA	6 Hz	1,000	Δ_{36}	Δ_{36}	No	0.10907.01	0.17950	$Y = \frac{X}{(A + BX)}$	0.705684	1702.833	0.22716
WES16	15 Hz	1,000	DYNA	6 Hz	1,000	Δ_o	Δ_o	No	0.65035+00	0.64026	$Y = \frac{X}{(A + BX)}$	0.320242	785.6067	0.64577
WES16	15 Hz	VAR	DYNA	6 Hz	1,000	DSM	Δ_o	Yes	0.21050+07	-0.81509	$Y = A + (\frac{B}{X})$	256.1803	0.839484	0.88510
WES16	15 Hz	VAR	DYNA	6 Hz	1,000	DSM	Δ_o	No	0.18511+07	-0.78348	$Y = A + (\frac{B}{X})$	217.1893	0.859020	0.87404
WES16	15 Hz	7,000	DYNA	6 Hz	1,000	Δ_o	Δ_o	Yes	0.61229+01	0.82687	$Y = \frac{X}{(A + BX)}$	0.123363	53.86[illegible]24	0.89081
DYNA	6 Hz	1,000	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.87276+00	0.84890	$Y = \frac{X}{(A + BX)}$	0.678184	514.8209	0.89838
DYNA	6 Hz	1,000	RR400	25 Hz	726	Δ_o	Δ_o	No	0.65244+00	0.83921	$Y = \frac{X}{(A + BX)}$	0.762566	440.3407	0.90055
RR510	25 Hz	1,600	DYNA	8 Hz	1,000	Δ_o	Δ_o	Yes	0.2935.+01	0.90660	$Y = \frac{X}{(A + BX)}$	0.505463	-200.1482	0.93692
RR510	25 Hz	1,000	DYNA	8 Hz	1,000	Δ_o	Δ_o	No	0.29894+01	0.89672	$Y = AX^B$	18.59170	1.258556	0.93218
DYNA	6 Hz	1,000	RR2008	25 Hz	1,800	Δ_o	Δ_o	Yes	0.52157+00	0.88610	$Y = \frac{X}{(A + BX)}$	1.509585	314.6532	0.90298
DYNA	6 Hz	1,000	RR2008	25 Hz	1,800	Δ_o	Δ_o	No	0.52141+00	0.84140	$Y = \frac{X}{(A + BX)}$	1.528219	297.9923	0.88431
DYNA	6 Hz	1,000	RR2008	6 Hz	1,000	Δ_o	Δ_o	Yes	0.85596+00	0.50403	$Y = \frac{X}{(A + BX)}$	0.638928	638.2677	0.74830
DYNA	6 Hz	1,000	RR2008	6 Hz	1,000	Δ_o	Δ_o	No	0.84324+00	0.43219	$Y = \frac{X}{(A + BX)}$	0.660887	580.5006	0.74443
RR2008	15 Hz	1,000	DYNA	6 Hz	1,000	Δ_o	Δ_o	No	0.95745+00	0.77686	$Y = \frac{X}{(A + BX)}$	[illegible]	633.4884	0.58065
DYNA	6 Hz	1,000	RR2008	15 Hz	7,000	Δ_o	Δ_o	Yes	0.69912-01	0.84590	$Y = \frac{X}{(A + BX)}$	5.729952	690.4603	0.86362
DYNA	6 Hz	1,000	RR2008	15 Hz	7,000	Δ_o	Δ_o	No	0.90131-01	0.79532	$Y = \frac{X}{(A + BX)}$	5.661394	666.7005	0.85709
DYNA	6 Hz	1,000	RR2008	15 Hz	7,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	Yes	0.10825+01	0.88091	$Y = A + (BX)$	0.052727	0.871639	0.88091
RR2008	15 Hz	VAR	DYNA	6 Hz	1,000	LDSM	Δ_o	Yes	0.12683+07	-0.57755	$Y = \frac{1}{(A + BX)}$	-0.000269	2.418168	0.82301
RR2008	15 Hz	VAR	DYNA	6 Hz	1,000	LDSM	Δ_o	No	0.11251+07	-0.56471	$Y = \frac{1}{(A + BX)}$	-0.000151	2.234621	0.77242
DYNA	6 Hz	1,000	BENK	--	10,250	Δ_o	Δ_o	Yes	0.22184-01	0.37548	$Y = \frac{1}{(A + BX)}$	420.[illegible]69	-333284.7	0.20799
DYNA	6 Hz	1,000	BENK	--	10,250	Δ_o	Δ_o	No	0.19790-[illegible]	0.35673	$Y = A + (BX)$	0.000607	0.004128	0.35673
WES16	15 Hz	7,000	DYNA	6 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.10735+01	0.86687	$Y = A + (BX)$	0.085837	0.8062626	0.86687
WES16	15 Hz	7,000	DYNA	6 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.71657+00	0.86182	$Y = A + (BX)$	-0.059634	0.8469102	0.86182

* Indicates 0.12942×10^7.
** Variable.

Table 17

PTRF Regression Analysis for the Model 400 Road Rater

Y			X			Comparison Parameters		Temperature Corrected	Line Through "0" Y = AX		Curve			
Device	Freq	Force	Device	Freq	Force				A	Correlation Coefficient	Equation	A	B	Correlation Coefficient
WES16	15 Hz	VAR**	RR400	25 Hz	726	DSM	Δ_o	Yes	0.10692+07*	-0.58548	$Y = A + (\frac{B}{X})$	28.75503	0.569388	0.78501
WES16	15 Hz	VAR	RR400	25 Hz	726	DSM	Δ_o	No	0.94167+06	-0.63621	$Y = A + (\frac{B}{X})$	-153.7506	0.757697	0.86642
WES16	15 Hz	VAR	RR400	25 Hz	726	LDSM	Δ_o	Yes	0.17485+07	-0.70105	$Y = A + (\frac{B}{X})$	629.3073	0.606988	0.82405
WES16	15 Hz	VAR	RR400	25 Hz	726	LDSM	Δ_o	No	0.15366+07	-0.69060	$Y = A + (\frac{B}{X})$	530.6398	0.698849	0.83037
WES16	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.10919+01	0.67304	$Y = A + (\frac{B}{X})$	0.000129	-2.624-07	0.74140
WES16	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	No	0.10686+01	0.62910	$Y = \frac{X}{(A + BX)}$	0.517817	455.9837	0.76224
WES16	15 Hz	7000	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.53156+01	0.74114	$Y = \frac{X}{(A + BX)}$	0.89971	106.9923	0.83760
WES16	15 Hz	7000	RR400	25 Hz	726	Δ_o	Δ_o	No	0.52165+01	0.67872	$Y = \frac{X}{(A + BX)}$	0.104826	89.64548	0.84920
WES16	15 Hz	7000	RR400	25 Hz	726	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.36283+01	0.76719	Y = A + (BX)	0.115557	2.390860	0.76719
WES16	25 Hz	1800	RR400	25 Hz	726	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.33828+01	0.70168	Y = A + (BX)	0.142911	1.874220	0.70168
WES16	15 Hz	1000	RR400	25 Hz	726	Δ_o	Δ_o	No	0.55552+00	0.51862	$Y = \frac{X}{(A + BX)}$	1.320018	478.3304	0.75454
RR510	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.25781+01	0.89891	Y = A(X ^ B)	1.344551	0.971955	0.91350
RR510	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	No	0.25566+01	0.89578	$Y = \frac{X}{(A + BX)}$	0.423415	-47.48719	0.93506
RR2008	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.16331+01	0.83537	$Y = \frac{X}{(A + BX)}$	0.407655	209.9041	0.87614
RR2008	25 Hz	1800	RR400	25 Hz	726	Δ_o	Δ_o	No	0.15873+01	0.80321	$Y = \frac{X}{(A + BX)}$	0.436732	188.3492	0.88836
RR2008	15 Hz	1000	RR400	25 Hz	726	Δ_o	Δ_o	Yes	0.92435+01	0.85713	Y = A(X ^ B)	2.868566	0.830747	0.86035
RR2008	15 Hz	1000	RR400	25 Hz	726	Δ_o	Δ_o	No	0.84074+00	0.69083	$Y = \frac{X}{(A + BX)}$	0.800582	427.0572	0.78736
RR2008	15 Hz	7000	RR400	25 Hz	726	Δ_o	Δ_o	No	0.89730+01	0.83438	$Y = \frac{X}{(A + BX)}$	0.111938	-6.236497	0.90268
RR2008	15 Hz	VAR	RR400	25 Hz	726	LDSM	Δ_o	Yes	0.97477+06	-0.50678	$Y = \frac{1}{(A + BX)}$	0.000304	1.403273	0.81470
RR2008	15 Hz	VAR	RR400	25 Hz	726	LDSM	Δ_o	No	0.82842+06	-0.66933	$Y = A + (\frac{B}{X})$	-160.3898	0.713526	0.86373
RR510	25 Hz	1800	RR400	25 Hz	726	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.25489+01	0.78902	Y = A + (BX)	-0.013531	2.691596	0.78902
RR2008	25 Hz	1800	RR400	25 Hz	726	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.32321+01	0.65364	Y = A + (BX)	0.08849	2.325669	0.65364
WES16	15 Hz	7000	RR400	25 Hz	726	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	1.6354	0.62823	Y = A + (BX)	0.0530103	1.366022	0.62823

* Indicates 0.10692×10^7.

** Variable.

Table 18

PTRF Regression Analysis for the Model 510 Road Rater

Y			X			Comparison Parameters		Temperature Corrected	Line Through "O" Y = AX		Curve			
Device	Freq	Force	Device	Freq	Force				A	Correlation Coefficient	Equation	A	B	Correlation Coefficient
WES16	15 Hz	VAR**	RR510	25 Hz	1800	DSM	Δ_o	Yes	0.40789+06*	-0.68051	$Y = A + (\frac{B}{X})$	-22.32160	1.595010	0.89725
WES16	15 Hz	VAR	RR510	25 Hz	1800	DSM	Δ_o	No	0.35912+06	-0.70756	$Y = A + (\frac{B}{X})$	-51.96783	1.755398	0.91034
WES16	25 Hz	1800	RR510	25 Hz	1800	Δ_o	Δ_o	Yes	0.42300+00	0.76026	$Y = AX^B$	0.026913	0.549058	0.79409
WES16	25 Hz	1800	RR510	25 Hz	1800	Δ_o	Δ_o	No	0.41624+00	0.61542	$Y = AX^B$	0.034529	0.588558	0.77657
WES16	15 Hz	7000	RR510	25 Hz	1800	Δ_o	Δ_o	Yes	0.20583+01	0.81845	$Y = \frac{X}{(A + BX)}$	0.224994	113.9694	0.89371
WES16	15 Hz	7000	RR510	25 Hz	1800	Δ_o	Δ_o	No	0.20321+01	0.76102	$Y = \frac{X}{(A + BX)}$	0.232045	108.5211	0.87607
WES16	15 Hz	VAR	RR510	25 Hz	1800	LDSM	Δ_o	Yes	0.67039+06	-0.78111	$Y = A + (\frac{B}{X})$	683.2396	1.504546	0.87536
WES16	15 Hz	VAR	RR510	25 Hz	1800	LDSM	Δ_o	No	0.58831+06	-0.76046	$Y = AX^B$	31.68957	-0.612870	0.82977
WES16	15 Hz	1000	RR510	25 Hz	1800	Δ_o	Δ_o	No	0.21573+00	0.60065	$Y = \frac{X}{(A + BX)}$	3.075588	646.6410	0.80311
RR510	25 Hz	1800	RR2008	25 Hz	1800	Δ_o	Δ_o	Yes	0.15665+01	0.84921	$Y = \frac{X}{(A + BX)}$	0.854550	-127.5480	0.91625
RR510	25 Hz	1800	RR2008	25 Hz	1800	Δ_o	Δ_o	No	0.15951+01	0.82273	$Y = \frac{X}{(A + BX)}$	0.885630	-157.9565	0.91703
RR2008	15 Hz	VAR	RR510	25 Hz	1800	LDSM	Δ_o	Yes	0.38838+06	-0.56845	$Y = \frac{1}{(A + BX)}$	0.000156	0.624550	0.84935
RR2008	15 Hz	VAR	RR510	25 Hz	1800	LDSM	Δ_o	No	0.34306+06	-0.57595	$Y = AX^B$	1.308169	-1.020376	0.83453
RR2008	15 Hz	1000	RR510	25 Hz	1800	Δ_o	Δ_o	No	0.28935+00	0.77711	$Y = \frac{X}{(A + BX)}$	1.025136	544.8482	0.83614
WES16	25 Hz	1800	RR510	25 Hz	1800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.12540+01	0.81040	$Y = A + (BX)$	0.164884	0.637674	0.81040
RR510	25 Hz	1800	RR2008	25 Hz	1800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.74858+00	0.69747	$Y = A + (BX)$	0.005798	0.731220	0.69747
WES16	15 Hz	7000	RR510	25 Hz	1800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.12985+01	0.77608	$Y = A + (BX)$	0.164297	0.692077	0.77608
WES16	15 Hz	7000	RR510	25 Hz	1800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.78820+00	0.70818	$Y = A + (BX)$	0.517193	0.6633318	0.70818
WES16	15 Hz	7000	RR510	25 Hz	1800	Δ_{36}	Δ_{36}	Yes	0.69990+00	0.52383	$Y = A + (BX)$	0.000144	0.287329	0.52383

* Indicates 0.40789×10^6.
** Variable.

Table 19

PTRF Regression Analysis for the Model 2008 Road Rater

Y			X			Comparison Parameters		Temperature Corrected	Line Through "0" Y = AX		Curve			
Device	Freq	Force	Device	Freq	Force				A	Correlation Coefficient	Equation	A	B	Correlation Coefficient
WES16	15 Hz	VAR**	RR2008	25 Hz	1800	DSM	Δ_o	Yes	0.68340+06*	-0.71542	$Y = A + (\frac{B}{X})$	-186.5170	1.375254	0.84663
WES16	15 Hz	VAR	RR2008	25 Hz	1800	DSM	Δ_o	No	0.61710+06	-0.75325	$Y = A + (\frac{B}{X})$	-302.9814	1.564393	0.87675
WES16	15 Hz	VAR	RR2008	8 Hz	1000	DSM	Δ_o	Yes	0.11574+07	-0.50898	$Y = A + (\frac{B}{X})$	87.94448	0.601496	0.73952
WES16	15 Hz	VAR	RR2008	8 Hz	1000	DSM	Δ_o	No	0.10159+07	-0.52653	$Y = A + (\frac{B}{X})$	-56.31965	0.711186	0.78972
WES16	15 Hz	VAR	RR2008	15 Hz	VAR	DSM	LDSM	Yes	0.89409+00	0.70140	$Y = AX^B$	8.969479	0.693922	0.84964
WES16	15 Hz	VAR	RR2008	15 Hz	VAR	DSM	LDSM	No	0.90188+00	0.69174	$Y = AX^B$	6.469671	0.739983	0.83123
WES16	15 Hz	VAR	RR2008	15 Hz	VAR	LDSM	LDSM	Yes	0.12840+01	0.68801	$Y = AX^b$	79.17050	0.445840	0.82595
WES16	15 Hz	VAR	RR2008	15 Hz	VAR	LDSM	LDSM	No	0.12755+01	0.67436	$Y = AX^B$	62.04567	0.477008	0.80483
WES16	15 Hz	1000	RR2008	8 Hz	1000	Δ_o	Δ_o	No	0.54188+00	0.46637	$Y = \frac{X}{(A + BX)}$	1.332956	550.0633	0.72815
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_o	Δ_o	Yes	0.54686+00	0.65440	$Y = AX^B$	0.058269	0.533020	0.87459
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_o	Δ_o	No	0.55976+00	0.81649	$Y = \frac{X}{(A + BX)}$	0.842838	112.5802	0.87139
RR2008	15 Hz	7000	RR2008	8 Hz	1000	Δ_o	Δ_o	No	0.80743+00	0.39619	$Y = \frac{X}{(A + BX)}$	0.672498	596.0584	0.68422
RR2008	15 Hz	1000	WES16	8 Hz	1000	Δ_o	Δ_o	No	0.71613+00	0.58335	$Y = \frac{X}{(A + BX)}$	0.477841	894.4959	0.76087
WES16	8 Hz	1000	RR2008	8 Hz	1000	Δ_o	Δ_o	Yes	0.91454+00	0.41927	$Y = \frac{X}{(A + BX)}$	0.613724	645.7661	0.58705
WES16	8 Hz	1000	RR2008	8 Hz	1000	Δ_o	Δ_o	No	0.93917+00	0.43847	$Y = \frac{X}{(A + BX)}$	0.708568	494.7462	0.62461
WES16	25 Hz	1800	RR2008	25 Hz	1800	Δ_o	Δ_o	Yes	0.63634+00	0.81014	$Y = AX^B$	0.085663	0.695084	0.82258
WES16	25 Hz	1800	RR2008	25 Hz	1800	Δ_o	Δ_o	No	0.64758+00	0.75834	$Y = AX^B$	0.137856	0.764378	0.79909
WES16	25 Hz	1800	RR2008	25 Hz	1800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.97539+00	0.67276	$Y = Ae^{BX}$	0.186971	1.521252	0.62025
WES16	8 Hz	1000	RR2008	8 Hz	1000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.80419+00	0.58090	$Y = A + (BX)$	0.146444	0.410575	0.58090
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	No	0.11464+01	0.64870	$Y = A + (BX)$	0.140316	0.710153	0.84870
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_o	Δ_o	Yes	0.54629+00	0.85390	$Y = AX^B$	0.0584756	0.5337899	0.87438
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_o	Δ_o	No	0.55976+00	0.81649	$Y = \frac{X}{A + BX}$	0.8428383	112.5802	0.87138
WES16	15 Hz	VAR	RR2008	15 Hz	7000	DSM	Δ_o	Yes	0.11144+06	-0.75864	$Y = A + (\frac{B}{X})$	25.49674	6.193122	0.92305
WES16	15 Hz	VAR	RR2008	15 Hz	7000	DSM	Δ_o	No	0.10122+06	-0.78464	$Y = A + (\frac{B}{X})$	1.157442	6.454212	0.92638
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_{36}/Δ_{18}	Δ_{36}/Δ_{18}	No	0.7684+00	0.77122	$Y = A + BX$	0.083[illegible]	0.585534	0.77122
WES16	15 Hz	7000	RR2008	15 Hz	7000	Δ_{36}	Δ_{36}	Yes	0.73382+00	0.36202	$Y = A + (\frac{B}{X})$	0.001558	-4.61-07	0.41115

* Indicates 0.68340×10^6.
** Variable.

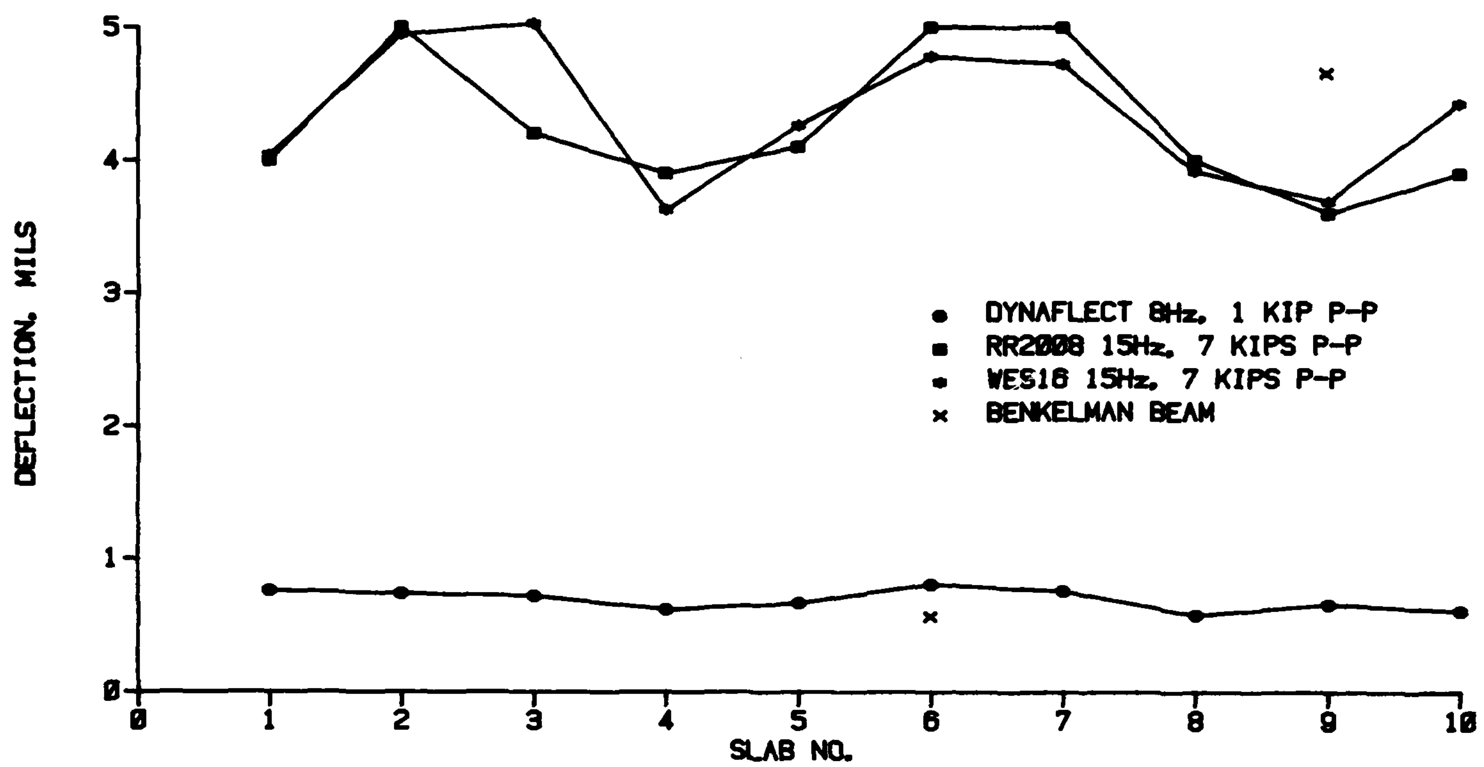

Figure 41. Deflection Δ_o for the PCC pavements
(1 mil = 25.4 microns; 1 kip = 4.448 kN)

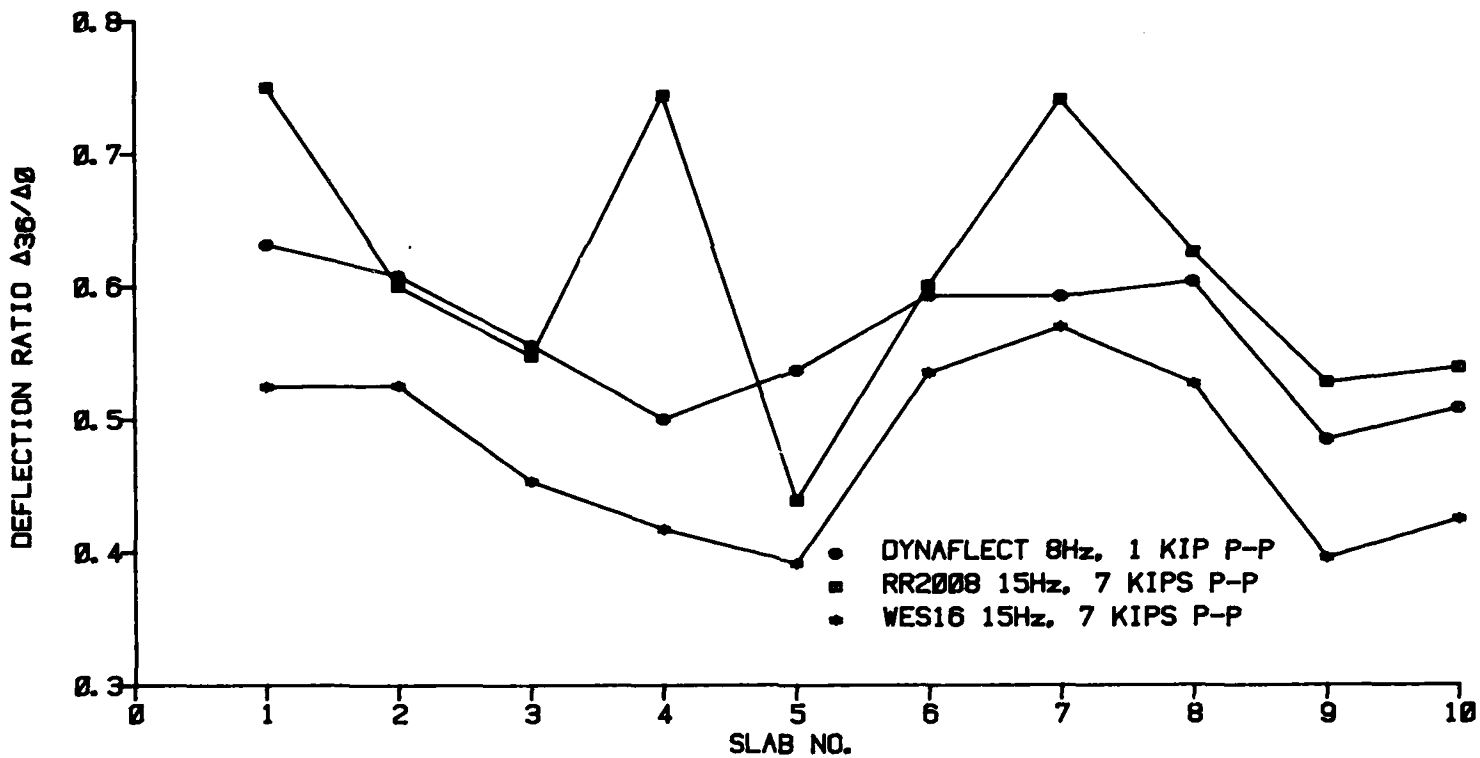

Figure 42. Deflection ratio Δ_{36}/Δ_o for the PCC pavements (1 kip = 4.448 kN)

the same trends as the WES 16-kip vibrator, whereas there is greater variability in the Model 2008 Road Rater. Figure 43 is the same type ratio except the deflection 18 in. (45.7 cm) from the load is used as a base. This 18-in. (45.7-cm) offset deflection is an averaged value for the Dynaflect and the Model 2008 Road Rater. The average is between deflections measured at 12 and 24 in. (30.5 and 61 cm) offset. Nevertheless, the Dynaflect again follows very closely to the WES 16-kip vibrator. Best-fit comparisons for these data were also conducted. Table 20 presents the results of these comparisons. The correlation coefficient for the Dynaflect and WES 16-kip data presented in Figure 43 is 0.93, which is very good, particularly for only 10 values. DSM measurements were also computed on the PTRF as shown in Figure 44.

Deflection basin tests were conducted on the PCC road at three locations with the FWD and the WES 16-kip vibrator. At two of the locations, the Model 2008 Road Rater was also used. Figures 45, 46, and 47 show the results of these tests. The tests were conducted first with the FWD. After the magnitude of the force was determined, the WES 16-kip vibrator and the Model 2008 Road Rater were tested as close as possible to that load. The comparisons of the WES 16-kip vibrator and FWD are very good.

OTHER SELECTED TESTS

In addition to tests on the PCC road, tests were conducted on selected AC pavements at the WES with the FWD, the Model 2008 Road Rater, the WES 16-kip vibrator, and in some cases the Dynaflect. Table 21 lists the properties of these pavement sections. The first area was on pavement traffic test section. Tests were conducted inside the traffic lane after the pavement had been subjected to 2700 coverages of a dual-tandem C-141 aircraft gear. There were also tests conducted outside the traffic lane adjacent to the tests located inside the lane. The outside tests designations will be preceded with an O and the inside preceded by an I. Figures 48 and 49 show Tests IS and OS. In each case, the impulse load of the FWD was matched as nearly as possible with the peak-to-peak load of the Model 2008 Road Rater and the WES 16-kip

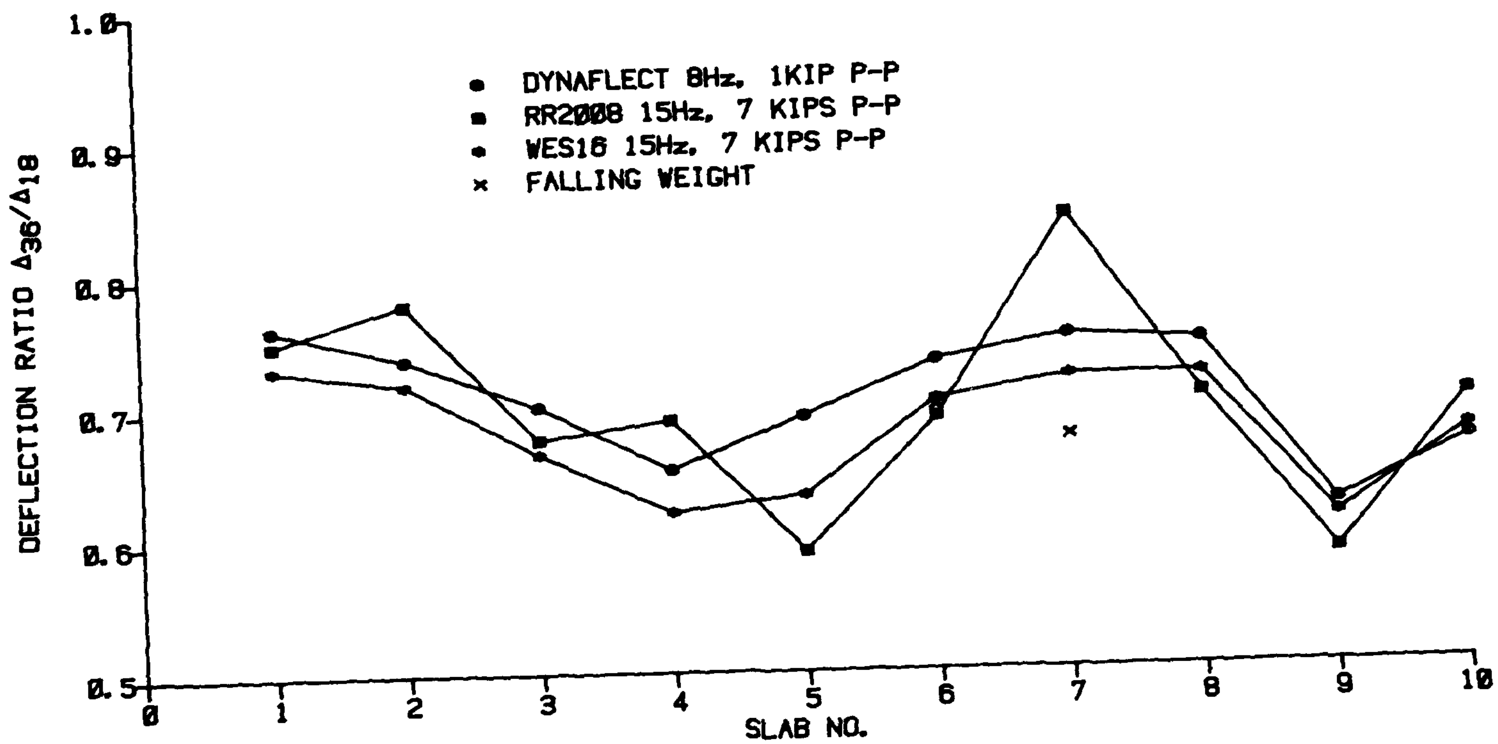

Figure 43. Deflection ratio Δ_{36}/Δ_{18} for the PCC pavements
(1 kip = 4.448 kN)

Table 20

Regression Analysis for PCC Pavements

[illegible]	[illegible]	[illegible]	Device	A Freq	A Force	Comparison Parameters		Line Through "0" Y = AX: A	Line Through "0" Y = AX: Correlation Coefficient	Curve: Equation	Curve: A	Curve: B	Curve: Correlation Coefficient
[illegible]		VAR**	DYNA	8 Hz	1,000	DSM	Δ_o	0.1890+07*	-0.6114	$Y = Ae^{BX}$	3148.6	-1252.1	0.6245
[illegible]	[illegible]	[illegible]	DYNA	8 Hz	1,000	Δ_o	Δ_o	0.6249+01	0.6235	$Y = A + BX$	0.001422	4.220	0.6235
[illegible]	[illegible] Hz	[illegible]	DYNA	8 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	0.8506	0.8849	$Y = \frac{1}{A + BX}$	5.081	-5.244	0.8905
[illegible]	[illegible] Hz	20,000	DYNA	8 Hz	1,000	Δ_o	Δ_o	0.1961+02	0.6457	$Y = A + BX$	0.004612	13.88	0.6457
[illegible]	15 Hz	20,000	DYNA	8 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	0.8513	0.8576	$Y = A + BX$	-0.07111	0.9771	0.8576
[illegible]	15 Hz	20,000	DYNA	8 Hz	1,000	Δ_{36}/Δ_{18}	Δ_{36}/Δ_{18}	0.9622	0.8033	$Y = A + BX$	0.2613	0.5937	0.8033
[illegible]	5 Hz	1,000	DYNA	8 Hz	1,000	Δ_o	Δ_o	0.1063+01	0.3515	$Y = A + \frac{B}{X}$	0.001127	-?.6481-07	0.3356
[illegible]	5 Hz	1,000	DYNA	8 Hz	1,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	0.6839	0.6668	$Y = A + BX$	-0.3381	1.282	0.6668
[illegible]	15 Hz	7,000	DYNA	8 Hz	1,000	Δ_{36}/Δ_{18}	Δ_{36}/Δ_{18}	0.9624	0.9285	$Y = A + BX$	0.04843	0.8941	0.9285
[illegible]	15 Hz	VAR	RR2008	15 Hz	7,000	DSM	Δ_o	0.3045+06	-0.8055	$Y = \frac{X}{A + BX}$	-3.4571-06	0.001584	0.8209
[illegible]	15 Hz	7,000	RR2008	15 Hz	7,000	Δ_o	Δ_o	0.1014+01	0.7666	$Y = A + \frac{B}{X}$	0.007812	-1.4601-05	0.7850
[illegible]	15 Hz	7,000	RR2008	15 Hz	7,000	Δ_{36}/Δ_o	Δ_{36}/Δ_o	0.7689	0.5851	$Y = \frac{X}{A + BX}$	0.6531	1.039	0.6435
[illegible]	15 Hz	VAR	RR2008	15 Hz	VAR	DSM	LDSM	0.8287	0.6143	$Y = \frac{X}{A + BX}$	0.7812	0.26341-03	0.6712
[illegible]	[illegible] Hz	1,000	RR2008	25 Hz	1,000	Δ_o	Δ_o	0.9212	0.1469	$Y = \frac{1}{A + BX}$	1274.4	-197312.0	0.1616
[illegible]	25 Hz	15,000	RR2008	25 Hz	1,800	Δ_{36}/Δ_o	Δ_{36}/Δ_o	0.6184	0.5054	$Y = A + BX$	0.1646	0.3594	0.5054
[illegible]	15 Hz	VAR	RR2008	15 Hz	VAR	LDSM	LDSM	0.6287	0.6149	$Y = \frac{X}{A + BX}$	0.78123	0.00026	0.6712
[illegible]	15 Hz	7,000	RR2008	15 Hz	7,000	Δ_{36}/Δ_{18}	Δ_{36}/Δ_{18}	0.9648	0.78978	$Y = \frac{X}{A + BX}$	0.50175	0.753566	0.8051

* Indicates 0.159×10^7.
** Variable.

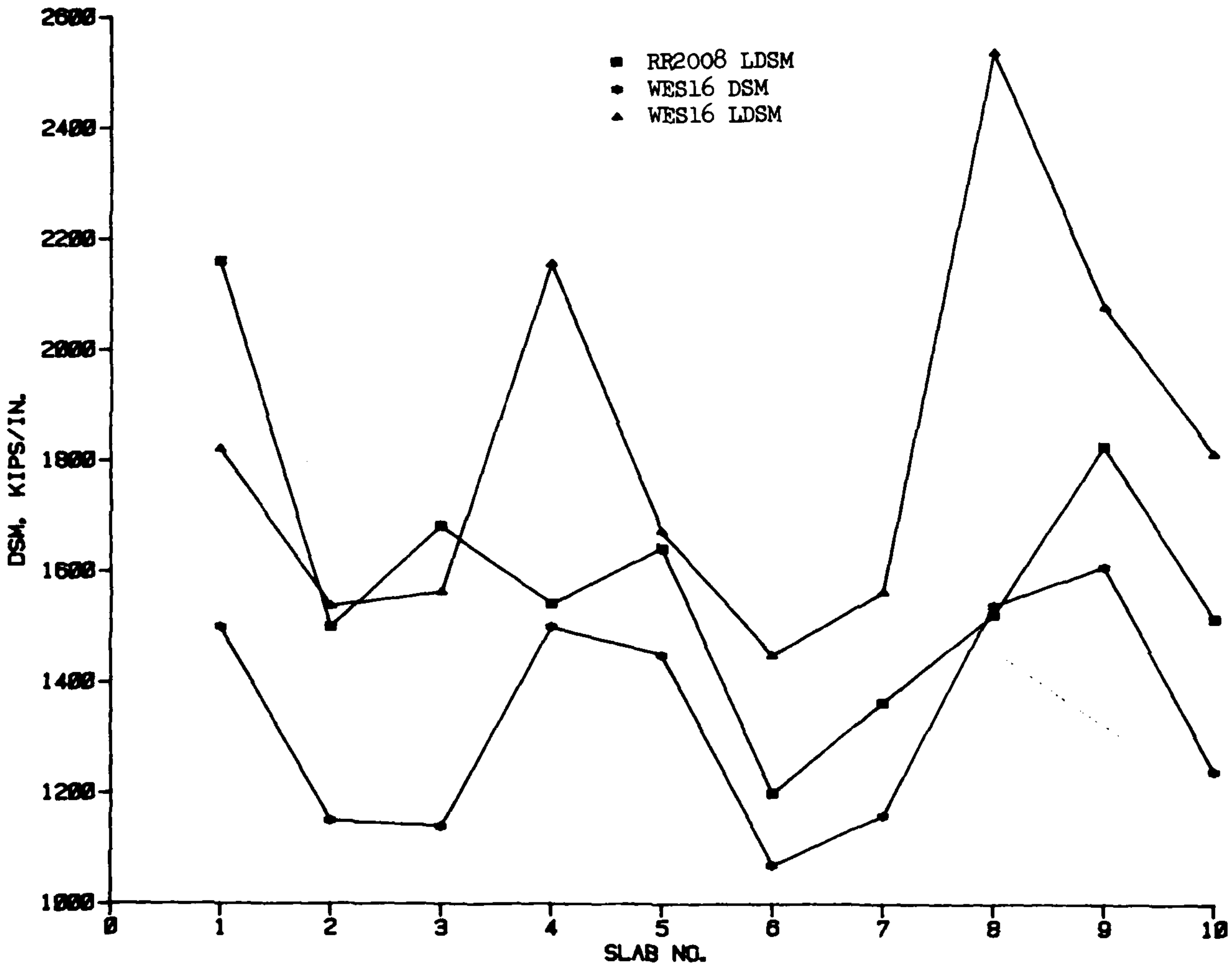

Figure 44. DSM comparisons on the PCC pavements
(kips/in. = 0.75 kN/cm)

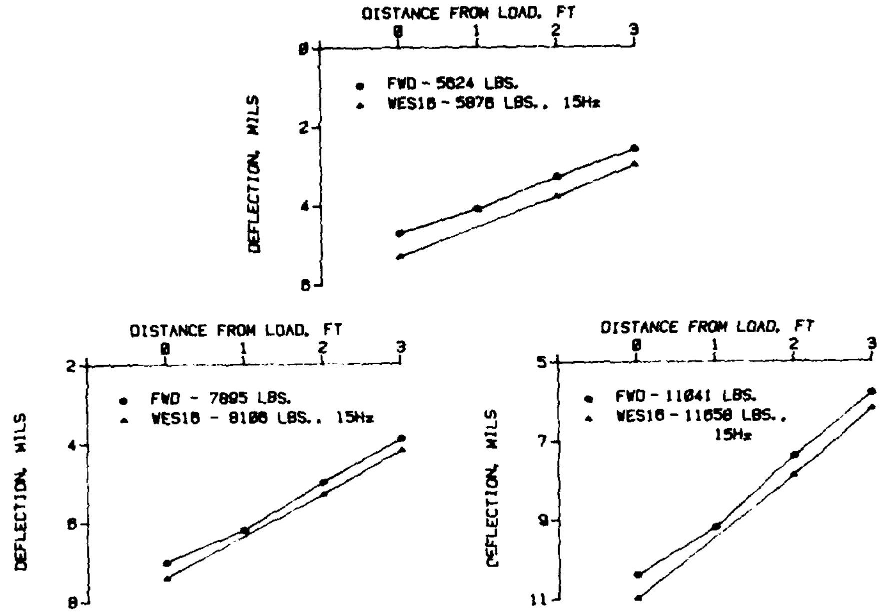

Figure 45. Deflection basins on Slab No. 6 of the PCC road (mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

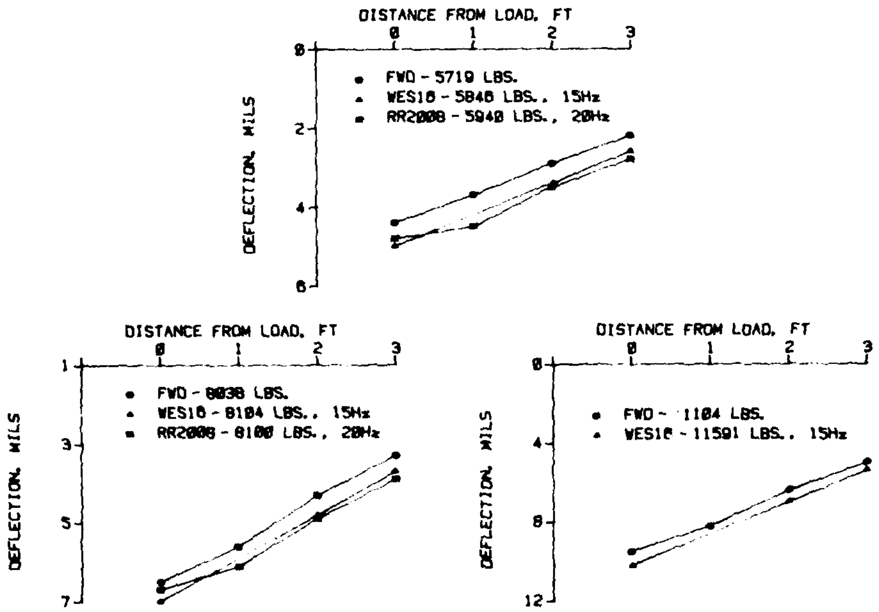

Figure 46. Deflection basins on Slab No. 7 of the PCC road (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

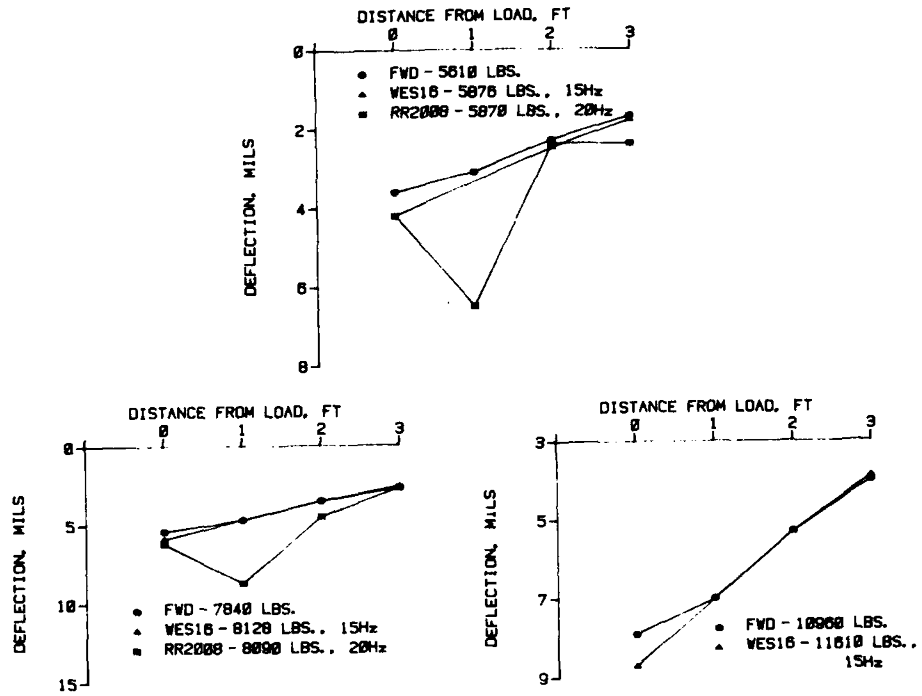

Figure 47. Deflection basins on Slab No. 11 of the PCC road (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

Table 21

Physical Properties of WES AC Pavements

	AC	Base Course		Subbase		Subgrade
Test Site No.	Thickness in.	Material	Thickness in.	Material	Thickness in.	Subgrade Material
A	3.9	Crushed stone	9.1	Gravelly sand	17	CL
S	3.5	Lime-stabilized clay-gravel	16.0	--	--	CL
G	1.5	6-in. cube sand-filled cells	6.0	--	--	CL
M	1.5	6-in. clayey gravelly sand	6.0	--	--	CL
P	1.5	MESL*	6.0	--	--	CL

Note: 1 in. = 2.54 cm.

* MESL = Membrane-encapsulated soil layer.

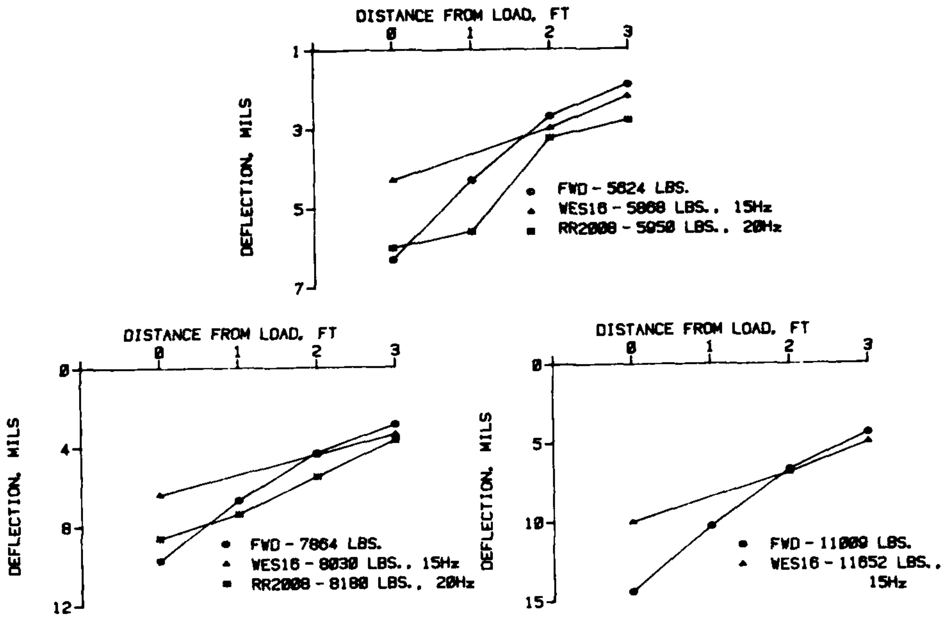

Figure 48. Deflection basin on test location IS (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

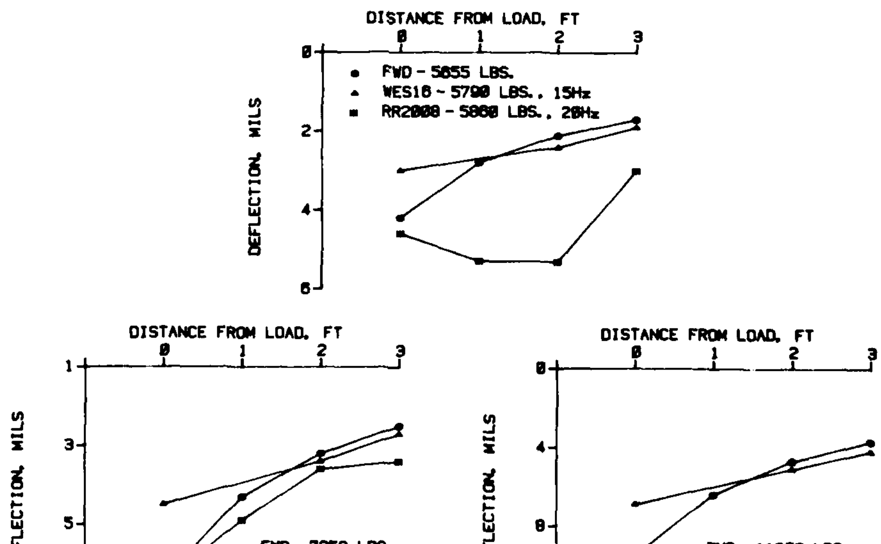

Figure 49. Deflection basin on test location OS (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

vibrator. Using data from Figures 48 and 49, the force level versus deflection could be projected through 0 so that deflections for the force level of the Dynaflect (1000 lb (4448 N)) could be interpolated. The results of these interpolations (Figures 50 and 51) indicate that on all of the tests, the WES 16-kip vibrator and FWD deflections agree with each other at distances of 2 and 3 ft from the applied load.

Tests on the conventional AC pavement, A, produced higher deflections (Figures 52 and 53), but again the basin data are consistent at distances away from the applied load. Additional tests on the weaker AC section (Table 21) produced the same results. Figure 54 presents the results for only the FWD and the WES 16-kip vibrator at higher loads.

In June 1978, an evaluation of Dulles International Airport (DIA) was made using both the Dynaflect and the WES 16-kip vibrator. The pavements at Dulles consist of 15 in. (38.1 cm) of PCC over a 9-in. (22.9-cm) granular base over a silty clay subgrade. NDT data from both the Dynaflect and the WES 16-kip devices were analyzed for the three runways at DIA. The testing with the Dynaflect consisted of deflection measurements at an 8-Hz frequency and 1000-lb peak-to-peak load. Two types of tests were conducted with the WES 16-kip device: (a) deflection at 20,000-lb (88.9-kN) peak-to-peak load and 15-Hz frequency, and (b) dynamic stiffness modulus (DSM) at 15 Hz with the load swept from 0 to 30,000 lb (133.4 kN) peak to peak. Approximately twice as many tests were conducted with the Dynaflect, but only data from the locations tested by both devices were used in this analysis. In this comparison, the WES 16-kip deflections will be reported in peak-to-peak values.

Tests at DIA were conducted at the center of the PCC slabs and adjacent to the transverse joints. Table 22 summarizes the results of regression analyses comparing data from the Dynaflect and WES 16-kip vibrator. Equations of the best-fit lines were determined by selecting the best correlation coefficient from six different curve equations from the curve-fit computer program. The correlations are based on 319 data points (159 center and 160 joint). The best agreement was obtained by

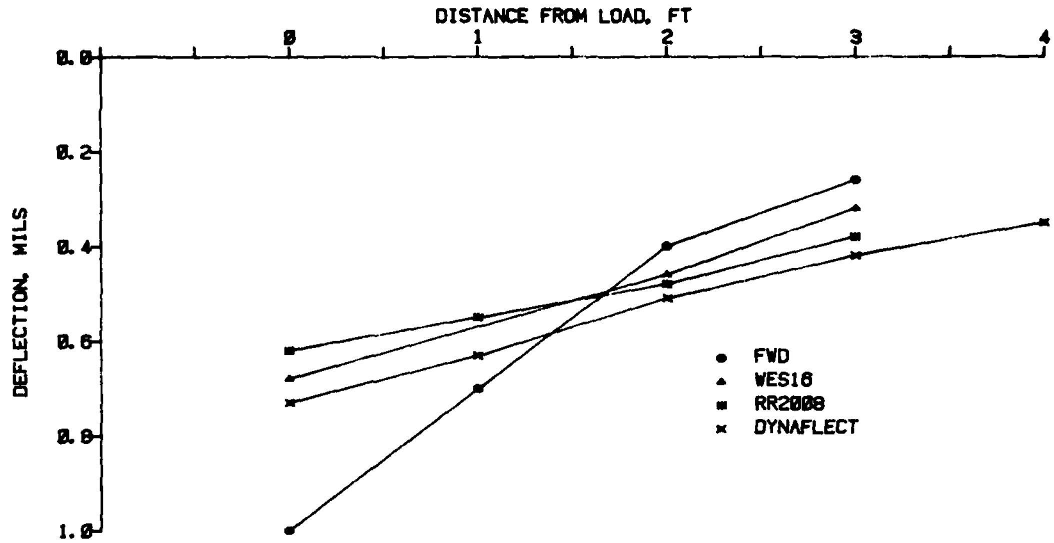

Figure 50. Dynaflect deflection basin and projected 1000-lb deflection basin for the FWD, the Model 2008 Road Rater, and the WES 16-kip vibrator on test location IS (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

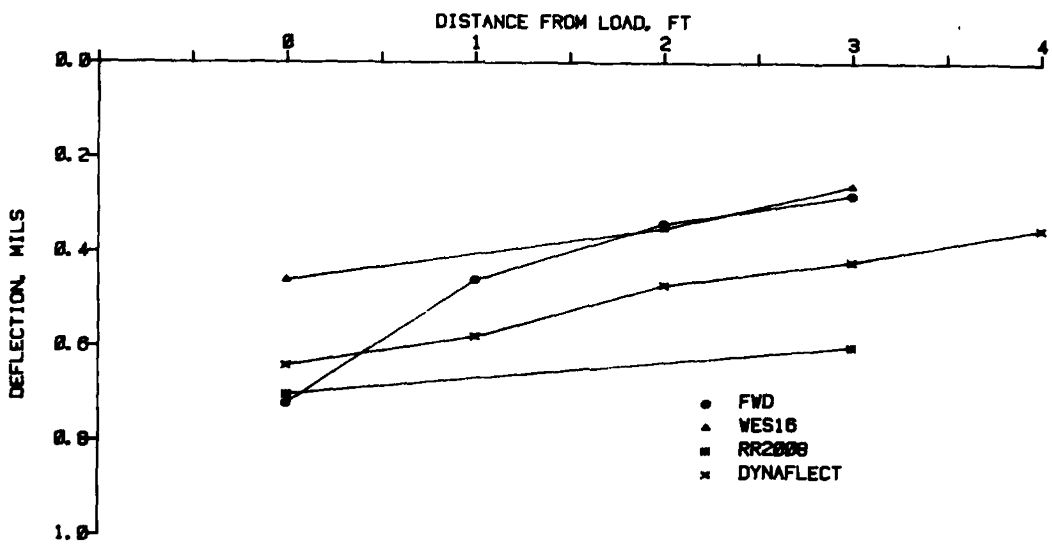

Figure 51. Dynaflect deflection basin and projected 1000-lb deflection basin for the FWD, the Model 2008 Road Rater, and the WES 16-kip vibrator on test location OS (1 mil = 25.4 microns; 1 ft = 0.3048 in.; 1 lb = 4.448 N)

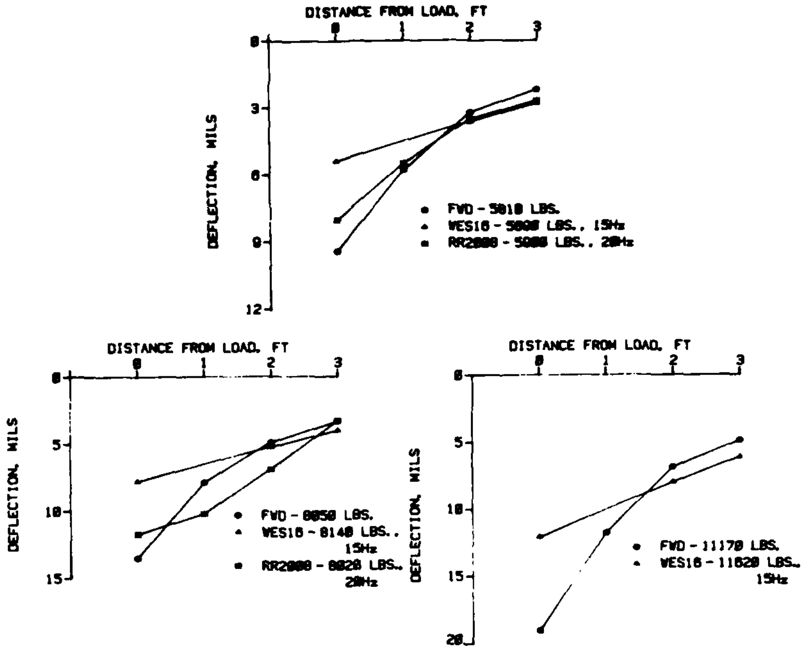

Figure 52. Deflection basins on test location IA (1 mil = 25.4 microns; 1 ft = 0.3048 m; 1 lb = 4.448 N)

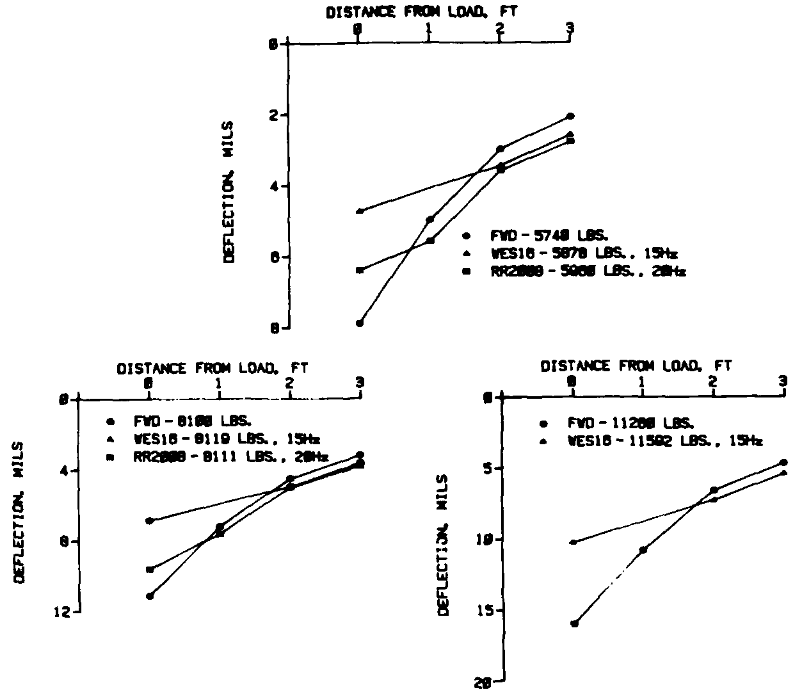

Figure 53. Deflection basins on test location OA (1 mil = 25.4 microns; 1 ft = 0.3048 m; 1 lb = 4.448 N)

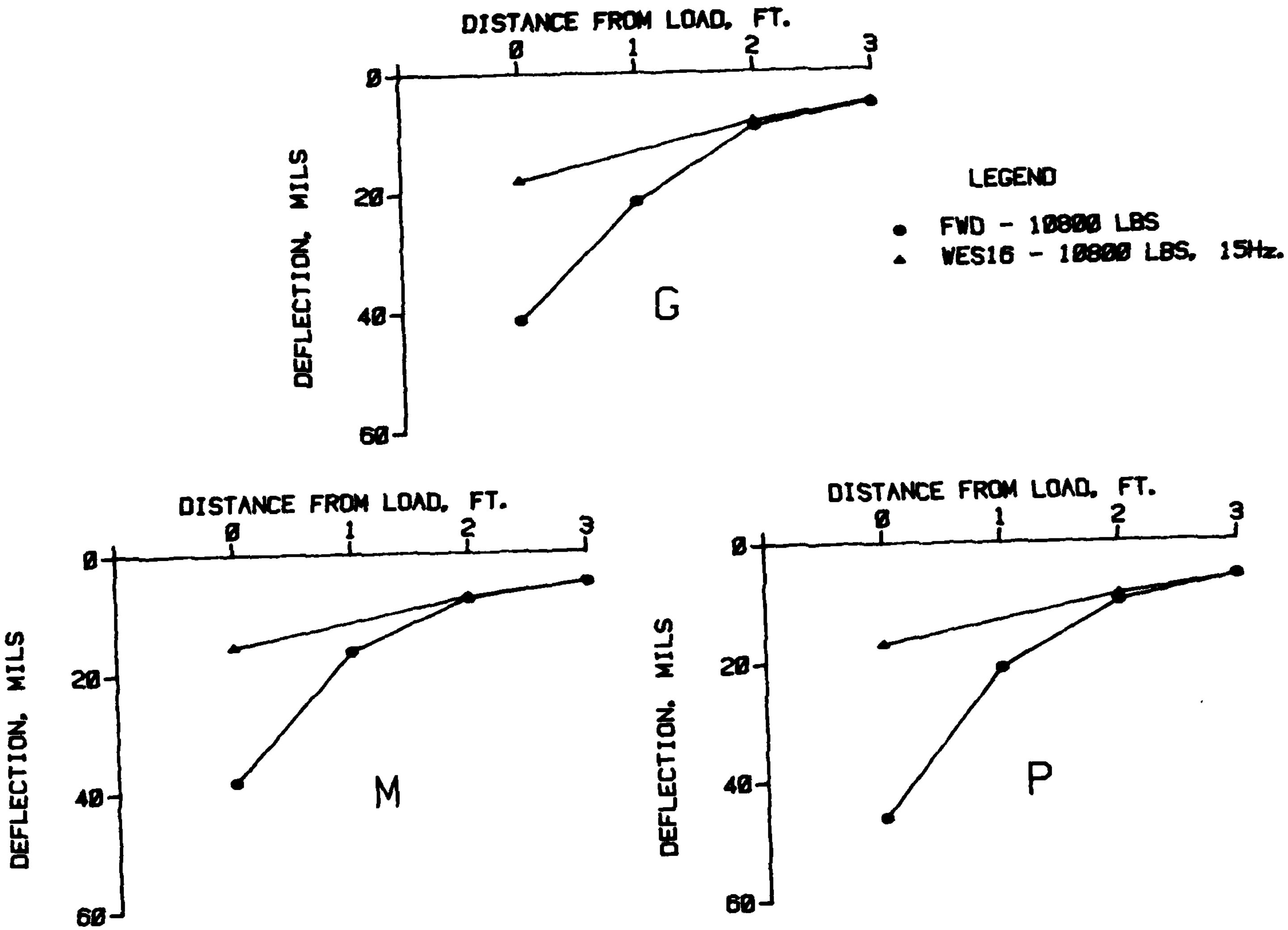

Figure 54. Deflection basins with the WES 16-kip vibrator and the FWD on weak AC pavements (1 mil = 25.4 microns; 1 ft = 0.3048 m; 1 lb = 4.448 N)

Table 22

Regression Analysis of Dulles Data

Type	Equation	Correlation Coefficient r	Standard Error
Runway			
Combined	WES 16-kip D1* = 0.00154 + 13.68 DYNAD1	0.76	0.000759 in.
	WES 16-kip DSM = 1/(8.6×10^{-5} + 0.682 DYNAD1)	0.73	1257 kips/in.
Slab Centers	WES 16-kip D1 = 0.00148 + 13.83 DYNAD1	0.52	0.000659 in.
	WES 16-kip DSM = 3453.4 + 0.3419/DYNAD1	0.50	1442 kips/in.
Transverse Joints	WES 16-kip D1 = 0.00174 + 12.88 DYNAD1	0.72	0.000847 in.
Taxiways			
Slab Center Averages	WES 16-kip D1 = 1/(439 - 7.33×10^{-5} DYNAD1)	0.52	0.000590 in.

Note: 1 in. = 2.54 cm; kips/in. = 1.71 kN/cm.
* D1 is the No. 1 sensor located on the 18-in.-diam plate on the WES 16-kip device and between the wheels on the Dynaflect.

combining all the 319 data points, which produced a correlation coefficient of 0.76. This is not considered a very good agreement. Data from the joints gave a higher correlation coefficient than the slab center data. This is probably explained by the fact that the deflections are larger at the joint. A very poor correlation was obtained using only the slab center data, and this is the location at which the evaluation tests are conducted.

ANALYSIS OF RESULTS

During this study, each of the candidate devices were evaluated based on six parameters. These included operational characteristics, which encompass ease, speed, and manpower requirements. The second parameter was cost, which was subdivided into initial cost and operating expenses. Accuracy was the third parameter. Both accuracy of force and deflection were considered. Transportability by cargo aircraft was fourth, the depth of measurable or significant influence was fifth, and suitability for testing light aircraft pavements was sixth. No weighting was given to any parameter, and each device was evaluated in as near the same manner as possible under the time and funding constraints.

The operational characteristics of the Dynaflect are better than any of the other candidate devices. The FWD could be improved if the pickups did not require hand placement.

Costs were evaluated based on a three-year life of the machine. It was assumed that an owner would conduct 20,000 tests a year (50 days at 400 tests per day). Based on this assumption and the time per test data in Table 2, the optimum manpower requirement in Table 3, and a $100 per day labor charge, yearly operating costs can be determined (Table 23). By adding the initial cost and the yearly operating cost for three years, total costs are compiled (Figure 55). Interest and inflation costs are neglected.

In the evaluation for accuracy of deflection and force, the rating is based on the accuracy at the frequency at which the vibrator is normally operated. For the Models 400 and 510 Road Raters, this is 25 Hz. For the Model 2008 Road Rater, the normal operating frequency is 15 Hz. The accuracy of the Benkelman Beam would be a function of operator's ability to obtain an accurate test axle load of 18,000 lb (8,165 kg), which is estimated to be within ± 1 percent. Table 24 summarizes the accuracy data.

Transportability by cargo aircraft did not differ for any of the trailer-mounted devices. The Benkelman Beam was the most transportable,

Table 23

Yearly Operating Costs

Device	Tests/Day	No. of Days/Year	Cost/Year
Benkelman Beam	150	134	$26,800
Dynaflect			
Digital	640	31	3,100
Standard	384	52	10,400
FWD	320	63	12,600
Model 400 Road Rater	480	42	8,400
Model 510 Road Rater	480	42	8,400
Model 2008 Road Rater	480	63	4,200

Note: Based on 20,000 tests per year and time per test in Table 2, optimum manpower requirements in Table 3, and a $100 per day labor charge.

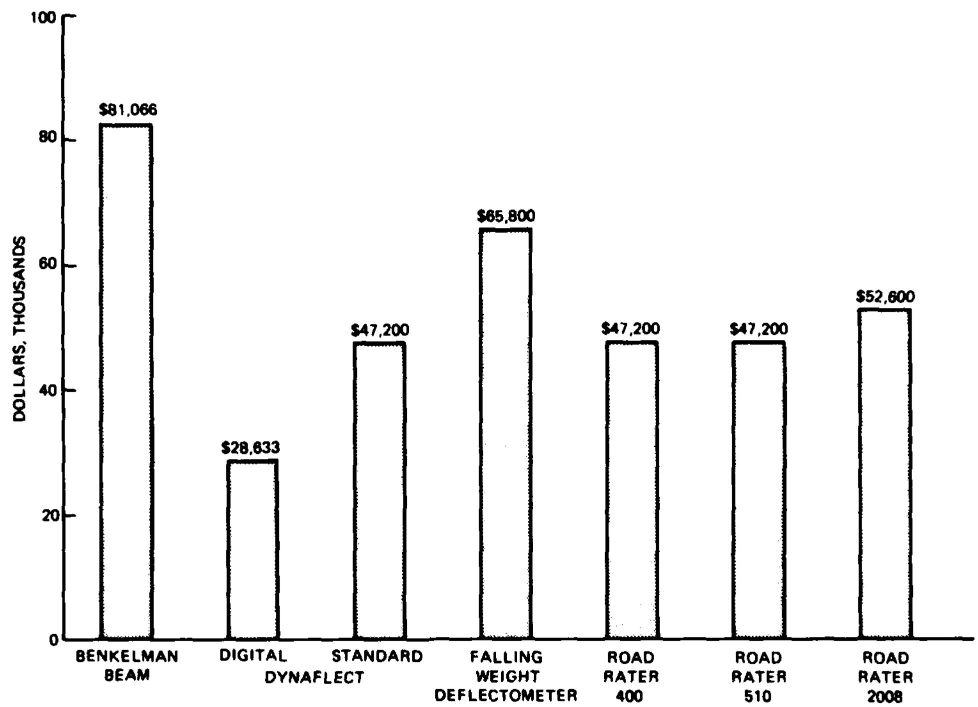

Figure 55. Three-year total costs

Table 24

Summary of Accuracy Data

Accuracy of Velocity Transducers/Deflection	
Device	Percent Error at Operating Frequency
Benkelman Beam	8.7
Dynaflect	5.5
FWD	5.1
Models 400 and 510 Road Raters	5.5
Model 2008 Road Rater	6.8

Accuracy of Applied Force	
Device	Percent Error at Operating Frequency
Benkelman Beam	N/A
Dynaflect	
Rigid Pavement	-4.2
Flexible Pavement	-12.9
FWD	-5.4
Models 400 and 510 Road Raters	-12.3
Model 2008 Road Rater	
Unfiltered	-8.3
Filtered	+1.0

whereas the Model 400 Road Rater was the least, due to being mounted on a truck.

Depth of influence evaluation is based primarily on the force output. The Models 400 and 510 Road Raters were not tested during this study, but data collected earlier with the Model 510 on 15-in. (38.1-cm) PCC indicated that its ability to load pavement at depth was more than the Dynaflect. The Benkelman Beam was ranked No. 1 because of surface deflection magnitudes.

The suitability ranking is based primarily on judgment and the correlations obtained when comparing experimental data with data collected with the WES 16-kip vibrator. Table 25 summarizes these comparisons. There were not enough data collected with the FWD to place it in these comparisons, but based on the limited data, the magnitude of the force, and the accuracy of the measurements, it was ranked high for suitability. The Benkelman Beam is rated last in suitability because of the low correlation results with the PTRF data. Also, the Benkelman Beam has not been reported as an evaluation tool for rigid pavements, possibly because the reference beam may be within the deflection basin and therefore will give erroneous results. The toe of the beam is only 8 ft (2.4 m) from the first reference support. On large slabs with the WES 16-kip vibrator, deflections of sufficient magnitude to affect an 8-ft (2.4-m) reference have been measured.

Another factor in the suitability ranking is the feature of being able to vary the dynamically applied force. It has been shown through resilient modulus testing that the modulus values of both subgrade and base materials are stress dependent. Therefore, in developing the evaluation methodology, the determination of this stress dependency by varying the dynamic load may prove to be an important factor. Based on these factors of correlations and variable force, the Model 2008 Road Rater and the FWD would rank best.

In order to analyze the results of the six evaluation parameters established for this study, a rating scheme was utilized, whereby each device was ranked in order of comparison with the other devices (Table 26).

Table 25

Summary of Regression Analysis Data

Device	AC Data Correlation Coefficients with WES 16-kip Vibrator			PCC Data Correlation Coefficients with WES 16-kip Vibrator		
	DSM vs Δ_o	Δ_o vs Δ_o	Δ_{36}/Δ_{18} vs Δ_{36}/Δ_{18}	DSM vs Δ_o	Δ_o vs Δ_o	Δ_{36}/Δ_{18} vs Δ_{36}/Δ_{18}
Benkelman Beam	0.24	0.26	--	--	--	--
Dynaflect	0.83	0.89	0.86	0.62	0.62	0.93
Model 400 Road Rater	0.79	0.84	0.63	--	--	--
Model 510 Road Rater	0.90	0.89	0.71	--	--	--
Model 2008 Road Rater*	0.92	0.87	0.77	0.82	0.79	0.81

* 15-Hz frequency, 7-kip peak-to-peak force.

Table 26

Ranking of Candidate Devices by Evaluation Parameters

	Benkelman Beam		Dynaflect		FWD		Model 400 Road Rater		Model 510 Road Rater		Model 2008 Road Rater	
Operational characteristics		6		1		5		3		4		2
Ease	6		1		5		3		4		2	
Speed	6		1		5		2		2		2	
Manpower	6		1		3		3		3		1	
Subtotal	18		3		13		8		9		5	
Costs		6		1		5		2		2		4
Accuracy		3		2		1		3		3		2
Deflection	6		2		1		2		2		5	
Force	1		4		3		5		5		1	
Subtotal	7		6		4		7		7		6	
Transportability by cargo aircraft		1		2		2		3		2		2
Depth of influence		1		5		2		6		4		3
Suitability		6		3		1		5		3		1
Totals		23		14		16		22		18		14

For the parameters that involved more than one evaluation, the parameter ranking was based on the sum of the particular evaluations. For example, accuracy was ranked based on the sum of rankings for accuracy of force and accuracy of deflections.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the results of this study, it is concluded that:

a. The Dynaflect rated best in operational characteristics, the Model 2008 Road Rater second, and the Benkelman Beam last.

b. When considering both initial and operating costs, the Dynaflect ranked best of all devices.

c. The FWD rated best in overall accuracy.

d. The Benkelman Beam rated best in terms of air transportability and the Model 400 Road Rater poorest.

e. The Benkelman Beam ranked best in the depth of influence and the Model 400 Road Rater poorest.

f. The FWD and the Model 2008 Road Rater ranked best under the evaluation parameter of suitability.

This study also evaluated three devices, the Dynaflect, the Model 2008 Road Rater, and the FWD, applicable for testing light aircraft pavement. The Dynaflect presently leads the group in cost and operational characteristics. Modifications to the Model 2008 Road Rater to improve its accuracy would improve its overall rating. Also, modifications to the FWD to allow mechanical placement of the velocity sensors would improve its rating. Further study with the FWD would likely cause a better rating for this device. The FWD was only tested for two days during the study.

RECOMMENDATIONS

It is recommended that three devices be considered in the development of the methodology for light airports: (a) the Dynaflect, (b) the Model 2008 Road Rater, and (c) the FWD. Furthermore, additional data should be collected with these three devices on rigid pavements and with the FWD on flexible pavements.

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